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Snowpack, Cloud-Seeding, and the Colorado River

A TECHNOLOGY ASSESSMENT OF WEATHER MODIFICATION

Leo W. Weisbecker

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Snowpack, Cloud-Seeding, and the Colorado River

Many small-scale experiments have been conducted in which winter clouds have been seeded to increase the snowfall in the high mountain areas of the Western United States. When the augmented snowpack melts in the springtime, it produces additional runoff that in turn is used to produce hydroelectric power as well as additional water for agricultural, municipal, and industrial uses. Now the Bureau of Reclamation is conducting a pilot project in the San Juan Mountains of Colorado to evaluate the effectiveness of this new technology. At the end of this five-year evaluation, the Bureau will be prepared to implement a large-scale Winter Orographic Snowpack Augmentation (WOSA) program throughout the Upper Colorado River Basin.

It seems almost a natural reflex to applaud and approve another attempt to improve on nature and create new water supplies, but more and more people today are expressing second thoughts. The public and the Congress are becoming increasingly concerned over the possible exploitation of technology without provisions for alleviating undesirable side effects.

Consequently, the National Science Foundation has initiated a Technology Assessment Program to operate in selected problem areas. Under this program Stanford Research Institute has explored the possibilities involved in developing a socially responsible WOSA program.

How does WOSA work; how effective will it be, and what will it cost? What will it do to the river flows and to the quality of the water? Can it be controlled to minimize hazardous conditions? Are there other ways of achieving the same effect? Who stands to gain and who stands to lose from WOSA and how much? What will it do to the environment and how will this affect living things, including man? What conditions can be put upon the project so that undesirable effects can be minimized?

(*Continued on inside back cover*)

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Foreword

THE MANAGEMENT of technology for the commonweal is, if not the central problem of our society, certainly an issue of paramount and expanding urgency.

To a substantial degree, the publics interested in any particular technology as well as decision-makers in the private sector and in the government find themselves forced to act, or at least take a stand, with inadequate knowledge of the technological alternatives and their possible consequences. The growing interdependence of our society on major technological developments, the incredibly large commitments of money and manpower, and the long period to realization for major projects all demand more reliable methods of forecasting and anticipating consequences of technology. The demands for foresight are exacerbated by the growing number of negative consequences of technology which could have been mitigated, moderated, or limited if effective early warning had been sounded.

Technology assessment, of which this study is one example, is the name for a class of policy studies intended to anticipate and explore the full range of consequences of the introduction of new technology or the expansion of an old technology in new and different ways. Men have always been interested in the consequences of technological development. One might reasonably ask, therefore, what's new about technology assessment? Several things are new.

First is the attempt to expand the study of the anticipated consequences well beyond the conventional considerations of

economic costs and benefits or immediate implications for the perpetrator or user of technology. The extension into the full range of social, economic, political, international, legal, and other societal impacts demands a degree of skill and sophistication rarely brought to the management of technology. The second feature of technology assessment is its focus as a policy study on informing the interested publics and the decision-makers of the possible range of consequences for new actions. Sound assessments should put into the hands of all interested parties reliable information to help them formulate their decisions and to generate more socially desirable management strategies. Furthermore, there should be cumulative benefits from making the discussions and the implementations of the management of technology far more sophisticated than they have been in the past. A third aspect of technology assessment is the attempt to organize and draw policy guidance from both what is known with some certitude and what is not known.

Normally one anticipates that policy flows out of knowledge; but in the effective management of technology, viable policies must flow out of both what we know and what we do not know. Consequently, one may anticipate that a technology assessment will lead to one or more of the following actions:

Modifying the project or technology to reduce disbenefits or to increase benefits

Defining a monitoring or surveillance program with regard to the technology as it becomes operational

Stimulating research and development to:

(a) Define risks more reliably
(b) Forestall anticipated negative effects
(c) Identify alternative methods of achieving the goal of the technology
(d) Identify feasible corrective measures for negative effects

Identifying regulatory or other control needs

Encouraging the legislative development of a technology into new areas to exploit anticipated benefits

Identifying needed institutional changes or innovation

Providing sound inputs to all parties at interest

Preventing a socially destructive technology from developing (an unusual but not impossible outcome)

The material covered in this book relates to many of these possible activities.

This particular study is one of many at various stages sponsored by the Office of Exploratory Research and Problem Assessment in the Research Applications Directorate in the National Science Foundation. The general goals of the NSF technology assessment program are:

To provide a substantive, comprehensive, useful input into public policy formulation and decision-making with regard to the application of particular technologies.

To explore and encourage technology assessment and the application of systematic methods, techniques, protocols, and approaches to complex policy-related problems

To encourage the growth of organizational capability to conduct impartial, comprehensive technology assessments

To encourage the expansion of the concept of impact analysis to include the impacts of social technology, social invention, and institutional change

To serve the growing needs in the federal agencies for advice, guidance, and assistance in technology assessment

To meet the mandated cooperative activities associated with the formulation of the Office of Technology Assessment by the Congress

With regard to any particular assessment of a technology, the sponsoring organization is faced by several difficulties: identifying organizations which can adequately perform the assessment; assuring that their methods, techniques, and strategies for conducting the study are adequate; not only assuring that the investigators have the widest latitude of independence, but also driving them to use their independence. An effective technology

assessment is likely to be bad news to someone. Consequently, that bad news as well as the good and indifferent news with regard to management of a particular technology must be brought forward in a way to inform the interested parties and illuminate the issues. In brief, quality control in the technology assessment must strike a balance between comprehensiveness, incisiveness, timelines, completeness, independence, and focus.

The history of this particular project may interest both general readers and other organizations interested in sponsoring such assessments, and will assist them in understanding how these goals were approached.

The study reported in this volume was initiated in January, 1971, in response to a request of July 15, 1970, from the Interdepartmental Committee for Atmospheric Sciences of the Federal Council for Science and Technology. They wished to explore the feasibility of applying technology assessment concepts to planned weather modification projects. The Bureau of Reclamation's proposal to augment the flow of the Colorado River by cloud seeding operations in the Upper Colorado River Basin was suggested by ICAS for the first technology assessment study, since a pilot experiment was already in progress in the San Juan Mountain Range and there was a need to provide the Secretary of the Interior and others with the necessary information to make the implementation decision. The National Science Foundation was requested to sponsor the study because it was already committed to the role of technology assessment under the RANN program and had no operational role to play with regard to the proposed project.

The selection of the Stanford Research Institute to conduct this technology assessment was made with the assistance of an ICAS committee based upon competitive proposals submitted by eleven different organizations. The request for proposals (RFP–71–101) was issued on August 4, 1970. A preproposal conference was held on August 18, 1970. Proposals were received by September 9, 1970. The contract was funded and monitored by the National Science Foundation. The Foun-

dation has recognized that independence of thought is an essential component of policy oriented research, and for this reason has given the contractor complete freedom in determining the substantive content of the report.

As the project drew to a close, interested ICAS agencies were given the opportunity to review the initial draft. Their comments were supplied to the contractor as a feedback mechanism. Reviews made it clear to both the investigating team and the reviewers that inadequate attention had been paid to some aspects of the economic analysis. Consequently, a supplementary award was made in late 1971 to permit the rounding out and completion of the study. A final draft of that report was received in July, 1972. One of the consequences of review of that report was the judgment that the work was of sufficient significance that a more popular or lay version of the document should be prepared that would carry the central elements of the study in a more readable form to a wider range of public interest groups, concerned citizens, legislators, government officials and others who might find the technical document beyond their need or understanding.

The preparation of that popular or lay version proved to be a more demanding task than either the contractor or the sponsoring agency realized. Four versions of that were prepared over a period of more than one year. The difficulty was in striking a balance between lucidity and brevity on the one hand and accuracy and completeness on the other. A final acceptable version was put forward in August, 1973. Each of these lay versions and the main report were reviewed by people not only with technical competence in the area, but with the editorial skill and perspective to evaluate its appropriateness for a more general audience.

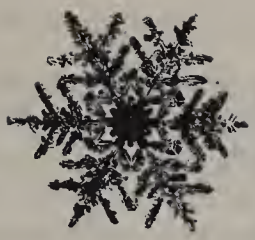
The delay in putting forward the complete technical report while awaiting the lay document was not a total loss of time, since the study team was available for and did conduct numerous briefings on the subject for professional, scientific and federal government organizations.

The report as it now stands reflects the findings and opinions of the contractor, and does not reflect the views or conclusions of any Federal agency including the Foundation. It should be read and evaluated in this context.

It is our hope and expectation that the report will be valuable at two levels. The first is that of moving the discussion forward with regard to the understanding of the snow enhancement projects being considered for the Colorado River Basin, by developing a more incisive and salient analysis of the effects, the means by which they may be determined, and the range and limitation of present and potential policy options. The second hope is that from the presentation of one operating model of how to grapple with an extremely complex question of exploring the full range of consequences of introducing a particular technology, others may learn to more reliably assess other technologies. Mr. Peter Wykoff, Program Manager for Weather Modification, in the Division of Environmental Systems and Resources, was joint monitor on this project until his recent retirement from the federal service. His professional, technical and administrative skills were crucial in the successful completion of this project.

JOSEPH F. COATES
Program Manager for Technology Assessment
Office of Exploratory Research
and Problem Assessment
National Science Foundation

Washington, D.C.
November 13, 1973



Acknowledgments

THIS BOOK is derived from a 600-page technical report prepared by Stanford Research Institute (SRI) for the National Science Foundation (NSF).* The study was conducted by a 20-person research team from SRI and the University of California at Davis. Their professional specialties represent meteorology, chemistry, engineering, economics, ecology, toxicology, sociology, and law. The team was assisted by a group of eminent consultants in the fields of meteorology, economics, and law. The appendix lists the study team members and consultants.

The final technical report was completed in May, 1972. The intervening period has seen a rapid change in the values of some resources in the Colorado River Basin. This has not altered the general findings of the study; however, events may move more swiftly than originally anticipated.

This popular version is intended to be as faithful as possible to the technical study report, but it tells only the basic story. The author bears responsibility for the selection of and emphasis given to the material, as well as any errors that may result from abstracting and condensing the study findings. The skillful editing of Ms. Shirley W. Hentzell of SRI was vital in producing an acceptable lay version. Ms. Marilyn Bagley of SRI did the original art work.

* *The Impacts of Snow Enhancement: A Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin*, Stanford Research Institute (University of Oklahoma Press, Norman, Oklahoma, 1974).

We are grateful to the NSF for the opportunity to bring this story to the many interested and affected parties. The NSF project monitors, Messers. Joseph F. Coates and Peter Wyckoff, established high standards for this effort, but they unhesitatingly met all requests for guidance and assistance in meeting them.

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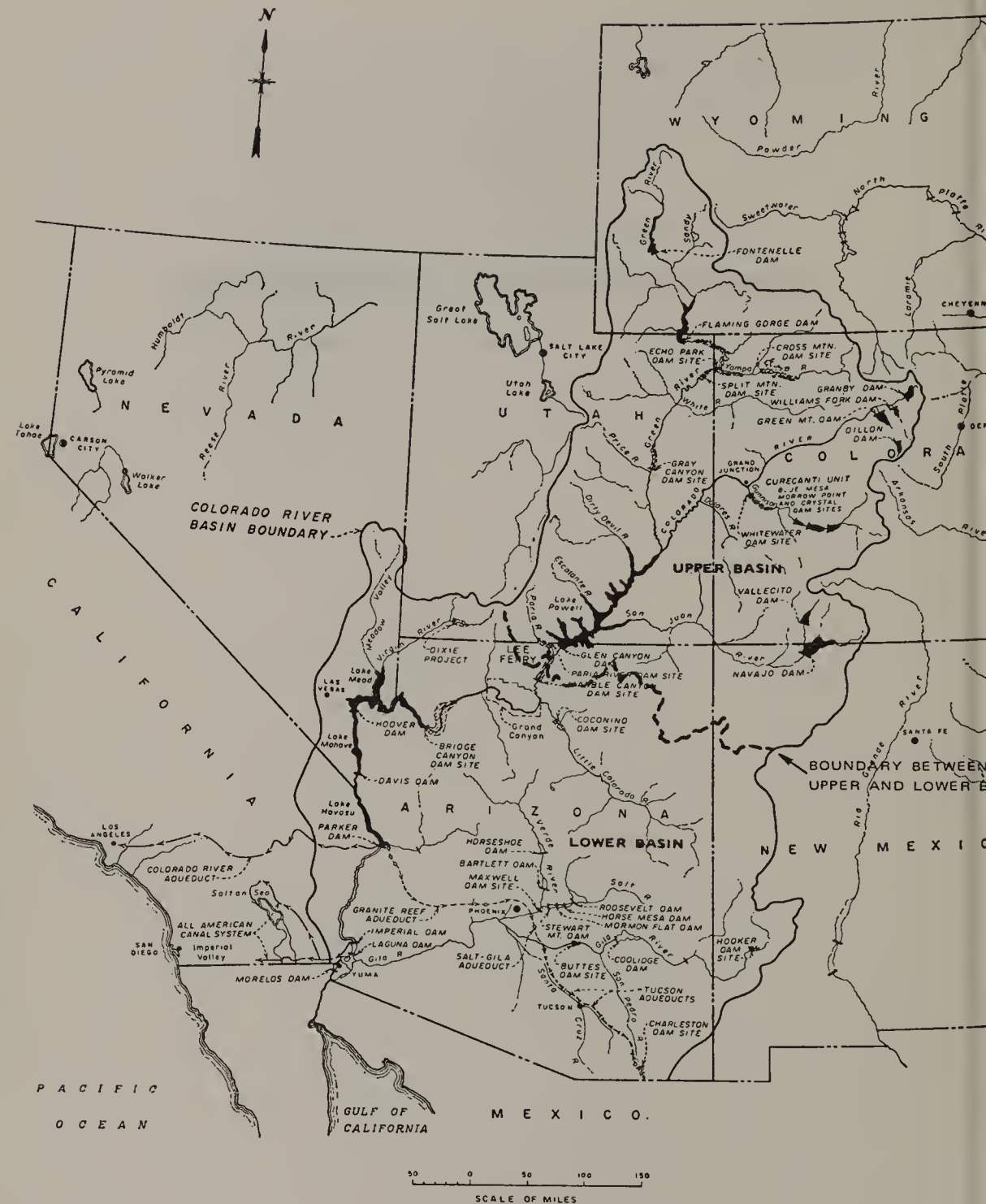
Snowpack, Cloud-Seeding, and the Colorado River



SOURCE: Lower Colorado River Basin Project hearings before the subcommittee o
Irrigation and Reclamation, 89th Congress 1st Session, Aug.-Sept., 1965
Serial No. 89-17-Part I.

SA-1

Colorado River Basin

Here Comes Weather Modification

RESPECTED scientists have been hard at work trying to modify the weather for at least 20 years. There are many different purposes for modifying the weather:

- Increasing or decreasing rain and snow in a location
- Reducing damage to crops and property from hailstorms
- Reducing the number of forest fires that are started by lightning
- Removing fog at airports so that planes may safely land and take off
- Changing the climate of a location
- Changing the intensity and direction of hurricanes so that they cause less destruction
- Reducing the destructiveness of severe thunderstorms and tornadoes

Varying degrees of success have been achieved in each of these areas, but in general modern technology has developed the science of intentional weather modification so that extensive operations will be possible in the next few years.

Most of these effects are achieved by seeding clouds with appropriate materials. The weather conditions at the time the clouds are seeded, the manner in which they are seeded, and the effects of the seeding are so different that weather modification is not one but several technical practices.

At the same time that people are working hard to learn how to modify the weather, some of man's activities are causing

unintended weather changes. For example, all of the following activities have without question resulted in weather modification, although the exact extent is unknown:

> Increasing the concentration of carbon dioxide and particles in the lower atmosphere by burning fuels in automobiles, power plants, and factories
>
> Contaminating the upper atmosphere with aircraft exhaust and rocket exhaust
>
> Changing the nature of large tracts of the earth's surface by clearing land and cultivating crops, and by putting up buildings and paving roads and parking lots

Inadvertent weather modification, although little understood, is a recognized by-product of industrial civilization.

Doing Something About the Weather

During the last four winter seasons (1970–71, 1971–72, 1972–73, 1973–74), several organizations under contract to the federal government have been collaborating in a program of seeding clouds in the San Juan Mountains of southwestern Colorado. This program is called a *pilot project*—that is, the purpose and the size are between those of an experiment and those of a full-scale operation. The Colorado River Basin Pilot Project will prove or disprove the results of previous short-term and small-scale experiments, over a much larger territory and for a longer duration. It is sufficiently large so that the costs and results can be scaled-up for an operation covering the entire Upper Colorado River Basin (Figure 1).

The idea behind the Colorado River Basin Pilot Project is a simple one. Most of the water supply of the Basin comes from the mountains where precipitation is abundant. (Large areas in the interior of the Basin where precipitation is low year-round contribute little water to the streams.) During the winter, the precipitation is mostly snow, which accumulates to great depths in the higher elevations. As temperatures rise in the late spring

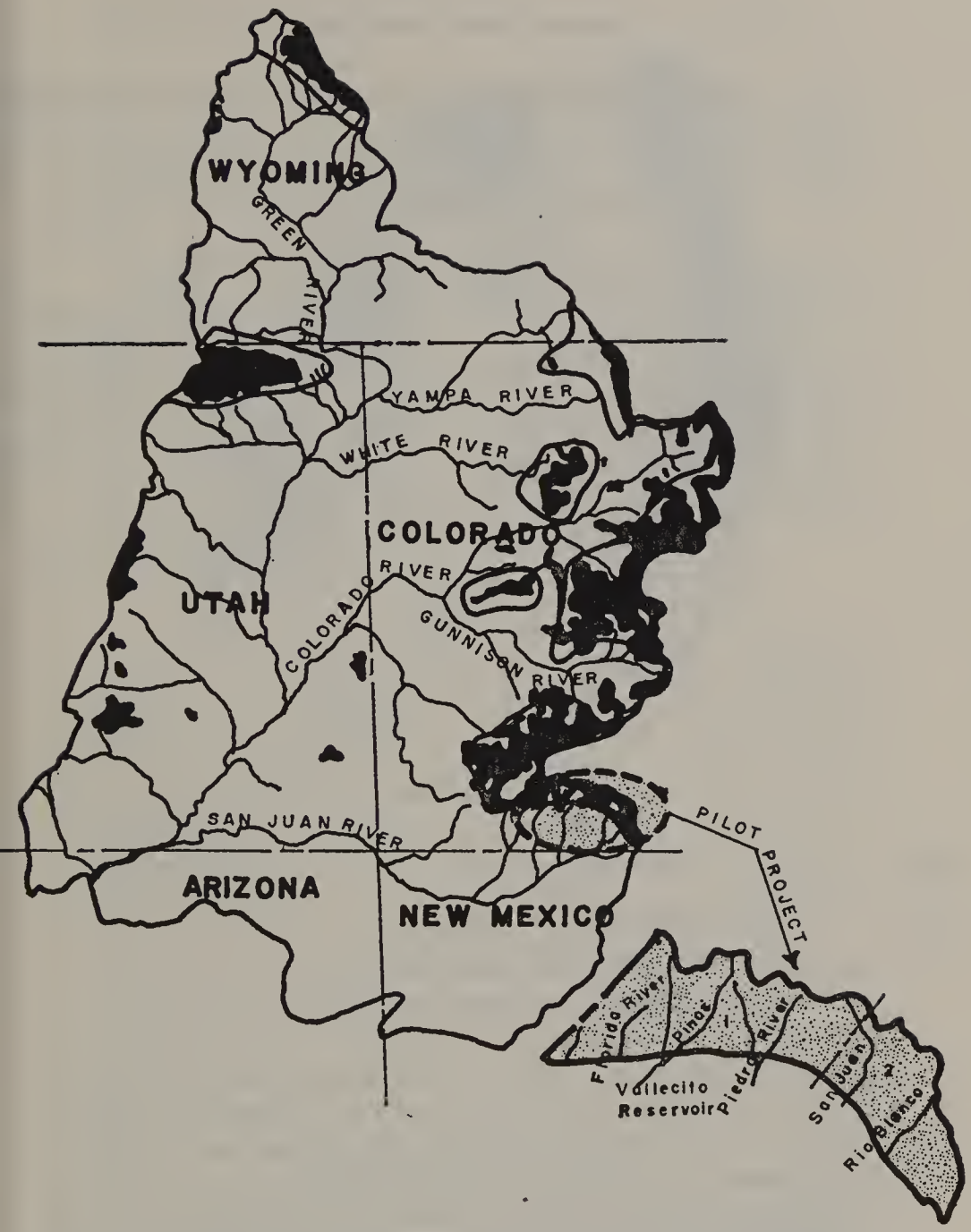


Fig. 1. The potential extent of an operational program in the Upper Colorado River Basin in comparison to the pilot project

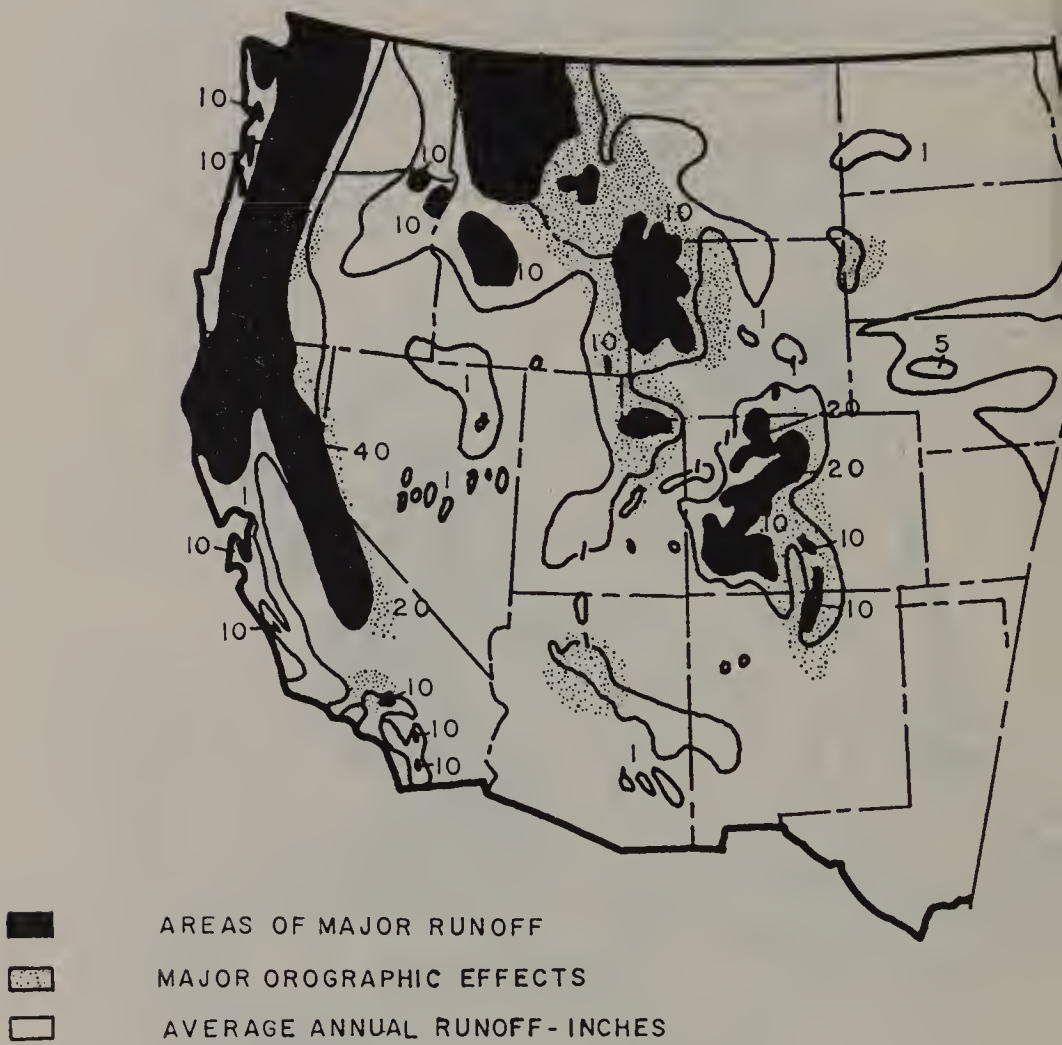


Fig. 2. Locations In the West where WOSA can be conducted

and early summer, the snow melts rapidly, causing the streams to rise. As the stored supply of snow is depleted, streamflow subsides. Summer rain in the mountains does not contribute much water to the streams. Therefore, if the winter snowfall in the high mountains can be increased, there will be more water in the streams of the Upper Colorado River Basin. Since the Colorado River supplies water to a large part of the arid South-

western United States, it seems desirable to increase this water supply if it is possible. It appears that a full-scale effort might increase the yearly water supply in the Colorado by 2.3 million acre-feet (enough to cover 2.3 million acres with one foot of water).

Experiments have shown that the kinds of clouds that produce winter season snowfall in the high mountain ranges in the West can be seeded with a chemical smoke under certain conditions to increase the snowfall. Clouds that form in mountainous regions are called orographic. These orographic clouds result when moist air masses from the Pacific Ocean are cooled as they are driven up over the mountains by prevailing easterly winds. We have named the process of augmenting the snow that accumulates in the mountains during the winter

Winter Orographic Snowpack Augmentation, or WOSA

The Colorado River Basin Pilot Project is carefully designed to provide high quality data concerning WOSA. Four to six winters of cloud seeding are expected to provide this kind of result. If the results are as favorable as many expect them to be, WOSA will most likely be expanded to the remainder of the favorable areas in the Upper Colorado River Basin within a few more years. There are also many other locations in the West where it is possible to increase the snowpack by cloud seeding. Since the desire for additional water supplies for irrigation, industrial, and municipal use is also widespread in the West, a successful operational WOSA program in the Upper Colorado River Basin could be expected soon to expand to most of the suitable locations (see Figure 2).

WOSA Is a Mixed Blessing

It seems almost a natural reflex to applaud and approve another attempt to improve on nature and create new water supplies, but more and more people today are expressing second thoughts.

This reaction is probably the result of widespread experience with many technical innovations that were enthusiastically adopted based upon an initial reaction to a need. Because we have often been disappointed by undesirable effects that were not foreseen, we have learned to respond to a proposal such as WOSA with a certain skepticism.

There seem to be two ways of dealing with any problems that an operational WOSA program in the Upper Colorado River Basin might create. We can try to foresee the problems and set conditions that would minimize them, or we can deal with the problems as they occur. We can avoid some problems if we ban the development or application of a technology that produces problems. If the project is stopped, the benefits are also lost. Only one way of dealing with potential problems shows any real promise: to anticipate the problems and then build the means and the motivation for minimizing them into the institutions that will develop and apply the technology.

One might ask how we go about developing a socially responsible WOSA program. First, we need to develop certain information about the program and the possible ways it might be implemented:

> How does WOSA work, how effective will it be, and what will it cost? What effects will the additional snowfall cause? What will it do to the river flows and to the quality of the water? Can it be controlled so that any hazardous conditions will be minimized? Are there other ways of achieving the same effect?
>
> What conditions would be put upon it by existing public policy? What problems would be solved or created by the laws and institutions that exist for dealing with weather modification and its effects, or the water supply that it would create in the Colorado River Basin?
>
> Who stands to gain and who stands to lose from WOSA and how much? Is it on balance a worthwhile project?
>
> What will it do to the environment directly and indirectly and how will this affect living things, including man?

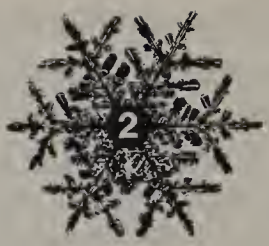
What do the people who might be affected think about it and how would they act to protect their interests?

What conditions can be put upon the project so that the undesirable effects can be minimized, redistributed, or compensated for by purposely redistributing benefits?

Given sufficiently detailed answers to these questions, we can all make sound decisions about what the WOSA program should be.

However, we will probably not be asked to participate in very many of the decisions that are made every day that can affect the quality of our lives. We have to use the means that we have in different situations to make our voices heard by the decision maker. The citizen has formal political channels to express his concerns, but he also has many informal channels. He can band together with persons of similar interests to offer a stronger voice. We have all seen many recent examples of the effectiveness of public action. Unless citizens make their voices heard, the public official will continue to make his decisions based upon *his* perceptions of society's needs and interests. Over time, these can become highly colored by the special interests who take the time and spend the money to make their desires known. If we work at it, there is no reason why average citizens cannot promote the public interest just as effectively as lobbyists and trade groups promote special interests.

The purpose of technology assessment is to inform those who help to make decisions concerning the development and application of technology of the consequences of the different kinds of decisions that they might make. Technology assessment will improve the public official's understanding of the public's needs and interests, so that he can make decisions based upon a broader range of interests. Technology assessment will put the public in a better position to make concerns known in a responsible and informed way. Concerns that are expressed in this way will be difficult to overlook at the level at which the decision is finally made.



How WOSA Works

DURING WINTER in the Upper Colorado River Basin—and throughout much of the Western United States—clouds are formed over the higher mountain elevations as storms pass over the terrain from a westerly direction. While the storms move generally eastward, the winds move in a cyclonic pattern counterclockwise about the center. In general, the lower the pressure, the stronger the winds around it.

Clouds and precipitation occur naturally in certain parts of the storm circulation. A cloud layer consisting of small water droplets exists in the vicinity of the low pressure storm center. These droplets are normally supercooled, remaining in the form of water even though they are colder than the temperature at which water normally freezes—zero degrees centigrade (0°C) or 32 degrees Farenheit (32°F). However, at temperatures colder than –20°C (–4°F), small ice crystals begin to form around "seeds" or "nuclei" that are present in the atmosphere. These "seeds" or "nuclei" are very small particles such as dust, smoke particles, or pollen grains given off by trees and flowers. Once ice crystals are formed, they tend to grow rapidly from the nearby water vapor and droplets. During their growth, ice crystals sometimes splinter and form additional ice particles, which can also grow. As the crystals become larger, they fall more rapidly and may eventually reach the ground as snow. The crystals can also grow by colliding and clumping together.

If the top of the cloud is warmer than –20°C (–4°F), then no part of the cloud in winter storms over the mountains will be

that cold, natural ice crystals will not form in large numbers, and little snow will fall.

In the 1940s, scientists found through laboratory experiments that the particles in silver iodide smoke will act as ice nuclei at temperatures considerably warmer than –20°C. These artificial nuclei can produce ice crystals in a cloud having cloud top temperatures between –10°C (14°F) and –20°C (–4°F). Therefore, by introducing silver iodide particles of the right size into these clouds, we can cause snow to fall where none would have occurred naturally.

Cloud-Seeding

The silver iodide particles must reach the insides of the clouds, and in the right numbers, if they are to produce snow. If there are too few nuclei, a few large ice crystals will form but not much snow will fall. If too many particles reach the clouds, a lot of very small ice crystals will be formed that will be carried over the mountain and melted back to water droplets as they reach the downdrafts on the far side; they will not fall as snow.

The most common method of producing silver iodide particles in mountainous areas is by ground-based generators. On release from a ground generator the very small particles spread out and rise much like smoke from a chimney. When the storm conditions are favorable for seeding, the low-level winds are stronger than usual and the silver iodide is rapidly dispersed. The silver iodide is lifted to the higher elevations, where it is effective, by the updraft at the upwind side of the mountain barrier (see Figure 3).

In the ground-based silver iodide generators in use today, the silver iodide is usually suspended as a fine dispersion in acetone. This combination is mixed under pressure with liquid propane and burned to produce a silver iodide smoke. The silver iodide produced by this type of generator loses its effectiveness as ice nuclei upon exposure to a few hours of sunlight. This does not limit its effectiveness in seeding winter clouds in

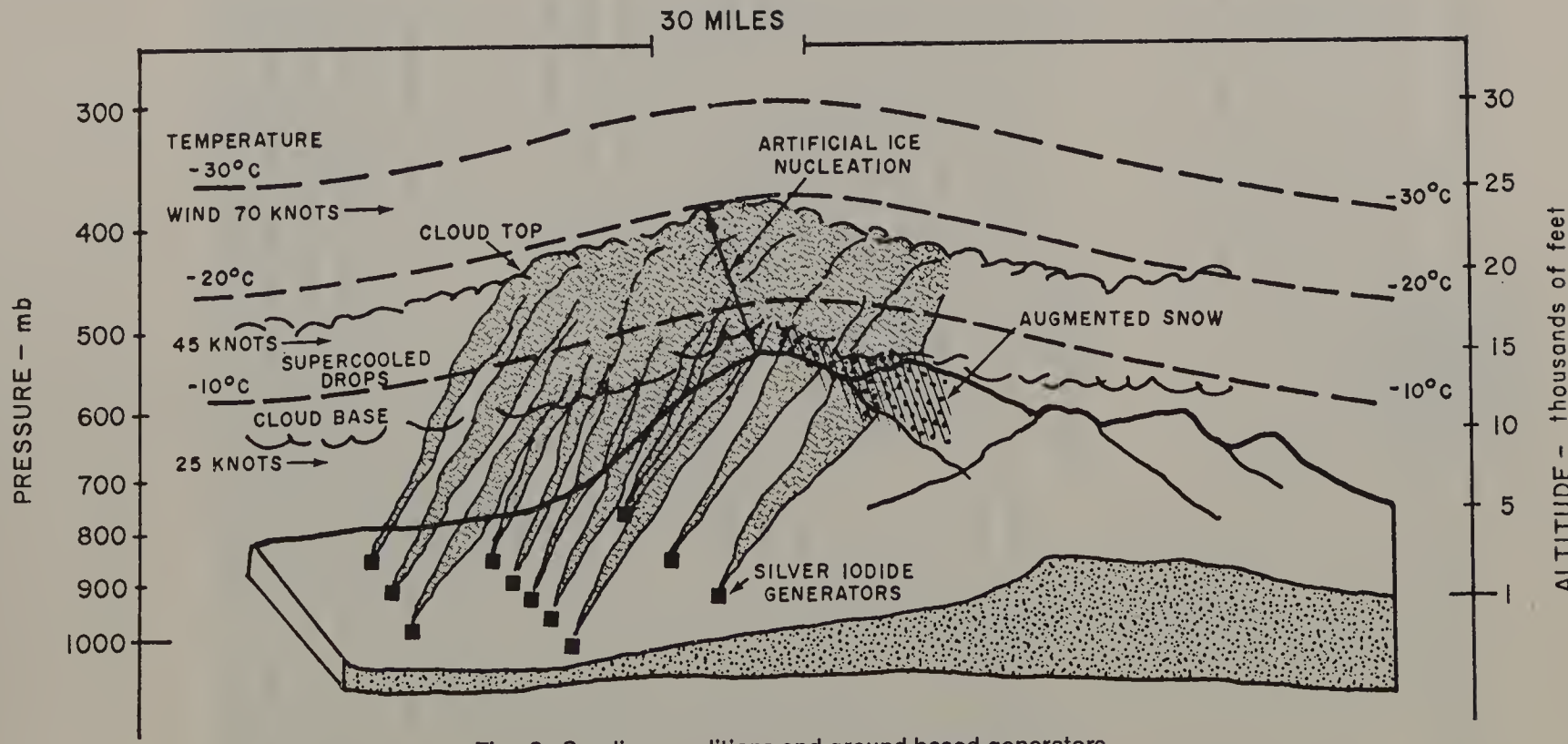


Fig. 3. Seeding conditions and ground based generators

the mountains from the ground, because skies are generally cloudy during seeding.

Proof that Cloud-Seeding Makes More Snow

It is not easy to prove just how much snow results from cloud-seeding. Snow that is produced by seeding looks just like natural snow. Since it all falls mixed together, even if seeded snow were different, it would be a difficult task to separate it and measure the different kinds. All we can do is measure the amount that falls at a specific place during a given time. Starting with this, we must find a way to measure the amount of precipitation added by cloud-seeding. The complicating factor is the great variability of natural precipitation.

In the first place, there are large changes in precipitation over short distances and so it is difficult to know whether a given snow measurement is representative of anything but the area in its immediate vicinity. The immediate vicinity may contain natural or man-made features that could greatly influence the amount of precipitation arriving at the gauge. Even more complicating is the natural variation in precipitation from storm to storm, even though the storms are otherwise very similar. Therefore we must go to statistical evaluations to try to distinguish between the effects caused by seeded and natural variations.

If we compare enough measurements that represent seeded precipitation with enough measurements of natural precipitation, the natural variations in the two sets of measurements will be so similar that the difference will represent that due to seeding. The trick is to take the two sets of measurements under as nearly similar conditions as possible. If the effect of seeding is much larger than the natural variation in precipitation, the number of measurements required to determine it will be fewer than if the effect of seeding is much smaller than the natural variation. Unfortunately, the WOSA situation is one in which seeding makes only a small difference compared with the natural

variations in snowfall for different storms, or the same storm in different areas.

Statistical methods would not be suitable for a full-scale WOSA whose goal was water production because they would halve the amount of water produced. To evaluate full-scale WOSA results, we could learn enough about the processes that affect precipitation so that the variability in precipitation in an area could be explained to some extent by physical principles. Some aspects of the growth of ice crystals, and the expected snowfall patterns, could be stated as mathematical formulas that include a simplified representation of terrain, seeding nuclei distributions, and meteorological conditions (such as moisture content and wind speed). The expected precipitation could be computed and compared with the actual measured results. Over time, the set of formulas (the model) would be adjusted until it could predict how much snow would fall with and without seeding, as determined by the statistical methods mentioned.

This very promising approach to the evaluation of an operational program is not yet a proven method. With the improvements that are coming along in our ability to measure snowfall accurately over a large area, the overall evaluation of a water production WOSA program will soon be possible. However, even if we can assess the effect of seeding over a large area for a given storm, or the effect of seeding over a smaller area for an entire winter season, we will not be able to say how seeding affected a single storm at a specific spot. It will be necessary to calibrate each target area initially, and perhaps periodically, using the statistical procedures described above.

WOSA in the Upper Colorado River Basin

THE STORM SYSTEMS that pass through the region in the winter take different paths and have different speeds, but they normally move from west to east. The most frequent storm path is to the north of Colorado. In such storms, the winds may blow out of the west over Colorado for several days. Snow falls on the mountain ranges that run from north to south. A second situation occurs with well-developed storms that pass directly through Colorado. The low level winds are initially from the south, but later turn to the west and northwest. In general, the snowfall amounts from such storms are large over most of the region. A third type of storm often remains stationary for several days, centered in Nevada or northern Arizona. These storms have winds from the southwest over Colorado. They bring relatively warm moist air over areas such as the San Juan Mountains in southwest Colorado, causing heavy snowfall.

Storm Tracks and Weather Patterns

In any given storm, snow occurs first in the western part of the region and gradually moves eastward. When snow is falling over the Rockies, the Plains States to the east are normally not experiencing precipitation and may even have clear skies. However, when the low-pressure center passes onto the plains, the storm may regenerate by drawing in warm moist air from the south. This air originally comes from the Gulf of Mexico. A new storm center may form southeast of Colorado that can bring large amounts of snow to the plains.

These storm systems that move across the region bring both natural precipitation and the conditions that provide opportunities for cloud-seeding. The amount of winter season—October through April—snowfall depends greatly upon the elevation. The average seasonal amounts vary from 5 inches of water equivalent or less in the river valleys to 30 inches of water equivalent over the highest mountain peaks. Ten to 15 inches of newly fallen snow is equivalent to one inch of water.

The winter season snowfall varies greatly from year to year. Over a long period, one-third of the years can be expected to show a snowfall higher by at least a third or lower by at least a third than the long-term average. The snowfall varies greatly from month to month during a season as well as from year to year. Heavy snowfalls frequently occur in March, near the end of the season.

In general over the area, a few days of heavy snowfall account for a large portion of the seasonal total. Five out of every hundred snowfall days account for about 25% of the total, while fifteen out of every hundred account for 50%. On the average, about one out of five winter days in the south (about 40 days every winter) and one out of seven in the northern portion of the region (about 30 days every winter) will be suitable for seeding. Suitable seeding conditions will last typically for about 4 to 6 hours.

The Snowfall Expected from WOSA

The research work that has been done and the experiments that have been carried out in the Upper Colorado River Basin tell us how much precipitation we can expect from different cloud conditions with properly conducted cloud-seeding. By applying this to the cloud conditions that occur during different parts of the winter, we can determine the increase in snowfall that can be expected.

This kind of analysis provides the following results:

Snowfall at elevations above 9,000 feet can be increased approximately 20–25% by seeding. This percentage increase is the basin-wide average. It would vary from about 15% in the drier northern-most part of the region to 25–30% in the wetter south. At elevations below 8,000 feet, the increase in snowfall would amount to less than one inch of water equivalent.

The increases are produced mainly by changing hours in which little snowfall would have occurred naturally into hours of significant snowfall. Cloud-seeding makes it snow longer, not harder.

The 20–25% increase in snowfall produced by seeding will be the same whether the season is wet or dry. We can't turn a dry year into a wet one because we can't raise that 20–25%.

Cloud-seeding will give a seeding target area a snowfall similar to the natural snowfall at an elevation 500 to 1000 feet higher. With cloud-seeding, the target area of Silverton, Colorado at an altitude of 9,300 feet would experience a snowfall as heavy as a natural snowfall at around 10,000 feet.

WOSA snowfall can be expected to vary from year to year and from one part of the region to another in exactly the same manner as natural snowfall.

Limiting Additional Snowfall

There may be reasons to limit the additional snowfall in a town or a drainage basin that would suffer undesirable consequences from too much snow. In that case, it might be desirable to limit the seasonal accumulation of snow in above-normal years to avoid spring flooding. However, weather patterns and storminess can be predicted for only a few days in advance. If long-range predictions were possible, so that one could know in advance that a winter would have natural heavy snows, seeding operations could be shut down entirely. If little snow were expected, all possible storms could be seeded. Since dependable long-range predictions are not available, the season to date is the main criterion. If snowfall were about average until late in

the season, then seeding would have been carried out during the winter. However, heavy late-season storms are common in the region, and could bring the total snowpack to undesirably high levels.

The decision to curtail or resume seeding depends on the level of risk that the snowpack represents. For example, in the San Juan Mountains the probability of flooding from snow melt runoff could be held to less than one year in 20 by curtailing cloud-seeding to only 90% of the potential increase in snowfall. This compares to the normal flood probability without cloud-seeding of one year in 25.

The probability of avalanches is greatly increased by heavy accumulations of new snow. In the region a few days of heavy snowfall give more than half of the seasonal snowfall, in both high and low snowfall years. Although seeding these storms would increase the avalanche risk, these are the storms on which seeding would be most effective. If seeding were curtailed on the basis of carefully monitored snowfall rates and accumulations in potential avalanche areas, the augmented snowfall could be reduced by as much as one-half. Fortunately, there are other ways of limiting avalanche risks.

Overseeding a storm likely to produce a natural snowfall should diminish the snowfall in a target area. However, there are many problems that must be overcome before this method is a practical way to prevent too large a snowpack.

The Basin's Share of the Atmospheric Moisture Supply

An initial reaction to cloud-seeding is that increasing the precipitation in one location necessarily reduces it in others. This both oversimplifies and distorts the effect of WOSA in the Upper Colorado River Basin, although it may apply to other types of cloud-seeding or to other locations.

The principal moisture source for winter storms in the Upper Colorado River Basin is the Pacific Ocean, including the Gulf of California. Part of the moisture is deposited as snow as

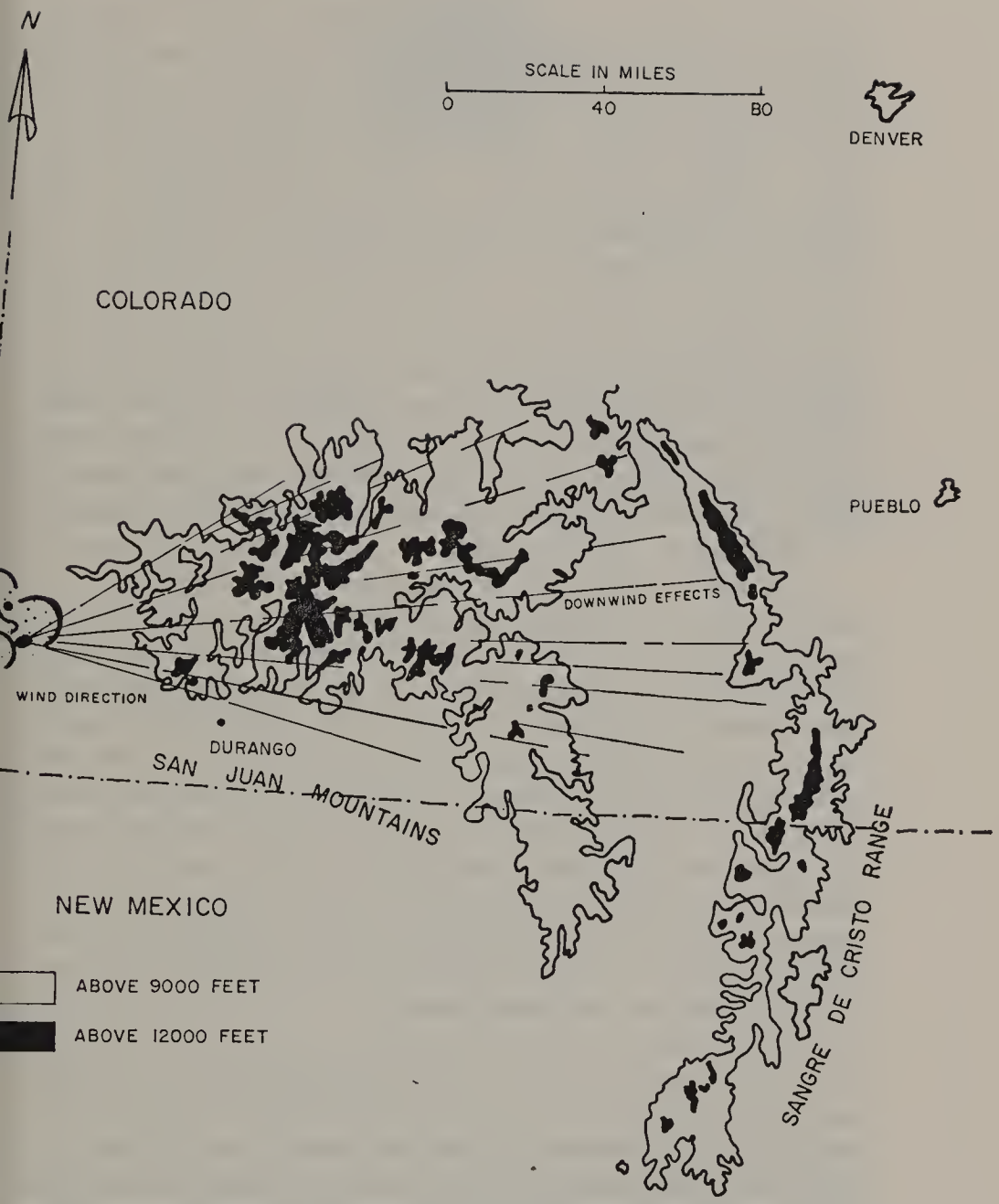
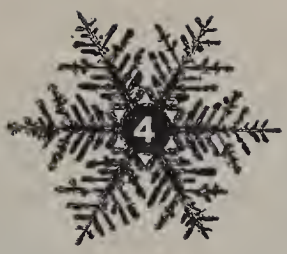


Fig. 4. Downwind precipitation augmentation in Sangre de Cristo Range from cloud-seeding in San Juan Mountains

the storms pass over the high mountains on their eastward journey. Once the air is lifted to a high elevation and has lost considerable moisture, it will not produce further precipitation by the same processes unless it is again lifted to the same elevation or higher. The Colorado Rockies are among the highest ranges encountered by the air in its eastward passage. After passing over the Rockies, the air descends over the plains and dries out as it warms up. It is highly unlikely that this dried air could produce precipitation over the plains, whether seeding had occurred over the mountains or not. The primary moisture source for winter precipitation over the prairie states is the relatively warm air that flows in from the Gulf of Mexico under favorable conditions. Because of the different natural sources of moisture for snow over the Colorado River Basin and over the prairies, cloud-seeding over the mountains will not measurably reduce the snowfall over the plains.

Weather modification investigators have found that silver iodide and the ice crystals that it produces can travel several hundred miles downwind on the air currents. These materials could seed storms that happened to be over the plains, and cause these storms to drop much more precipitation than they would under natural conditions. If this happened to a storm over Denver, the resulting heavy snowfall would cause serious and widespread inconvenience. Undesirable downwind cloud-seeding could be minimized if the silver iodide generators were turned off when favorable conditions in the mountains ended. During most of the time that seeding is effective over the mountains, conditions over the plains are unfavorable for seeding, with good weather conditions there.

Mountainous areas that are up to 150 miles downwind from a target area will also be affected by seeding. For example, seeding in the San Juan Mountains during southwest winds probably affects the snowfall over the Sawatch range. With west-southwest winds, seeding the San Juans will produce additional snow over the Sangre de Cristo Mountains (see Figure 4).



Snowpack, Runoff, and Streamflow

THE Upper Colorado River Basin covers about 109,500 square miles, but only some of the area is suitable for WOSA. In general, suitable areas are those with heavy natural snowfall. We have seen that the effectiveness of WOSA can be expressed as a constant proportion of the natural snowfall—about 20–25%. The natural snowfall increases with elevation.

Areas Suitable for WOSA

As a practical matter the areas where WOSA is effective are the elevations above 9,000 feet. In an average winter, precipitation will exceed 10–15 inches water equivalent at 9,000 feet or above, and WOSA would add at least 2 inches water equivalent at or above that level. The most suitable areas for WOSA are the mountain ranges that form the western and eastern boundaries of the Upper Basin. The western ranges are generally lower, less rugged, and not as extensive as the eastern ranges that form the Continental Divide. These mountain boundaries outline the river basin watershed, where water from snowmelt or rain flows through a system of tributary streams to one central river (see Figure 5).

The mountain ranges that outline the region are not continuous. They are oriented in different directions and they have different elevations and other surface features. They are spread out over such a great distance that each can experience unique weather conditions as a storm moves through the region. The

Fig. 5a. The Upper Colorado River Basin—Expected increases in snowfall from WOSA: Expected increases in snowfall (in equivalent inches of water) for a year having a normal number of seeding opportunities

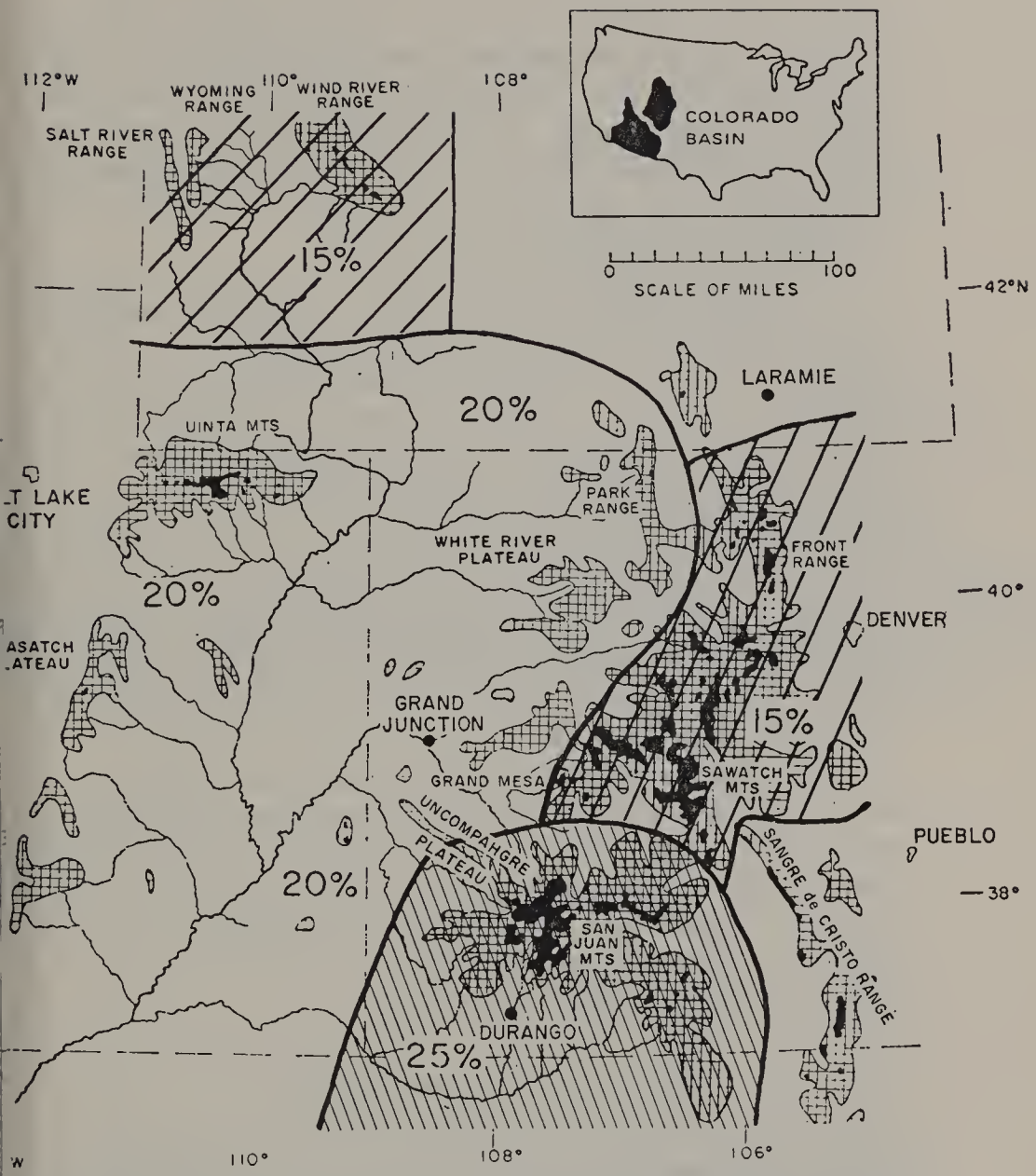


Fig. 5b. The Upper Colorado River Basin—Expected Increases in snowfall from WOSA: Expected Increases in snowfall that can be produced by cloud-seeding. The area of Interest shows topography above 9,000 feet (cross-hatched) and 12,000 feet (solid)

conditions that would be suitable for cloud-seeding would not occur at the same time throughout the region. In addition, the seeding conditions that would produce the best results would differ from range to range. An operational WOSA program in an area as large as the Upper Colorado River Basin cannot be one massive basin-wide operation; instead, it must combine and coordinate a great many separate operations.

The area that is suitable for cloud-seeding can be divided into ten districts, each small enough to have fairly uniform weather as a storm passes through the Upper Basin. Silver iodide smoke generators will be located at fixed positions upwind of each target area. The number of generators will depend upon the size of the target area, and the locations will be chosen to make the generators effective under the weather conditions that bring most of the seedable storms to the target area. The generators can be turned on or off and can be operated at either of two pre-set burning rates. Each district will have several generators to control, and the trick is to know which ones to operate at which burning rate to achieve the best possible cloud-seeding results. Because weather conditions can change so rapidly, it is necessary to re-evaluate the situation at least every hour.

The generator operating decisions are made on the basis of cloud top and mountain top weather conditions—wind speed and direction, temperature, barometric pressure, and humidity —and the concentration of ice nuclei. If no more snow augmentation is wanted in a target area, the generators can be switched off. This requires an elaborate information and control system such as that sketched in Figure 6.

From the Mountains to the River

In an average year, around 93 million acre-feet of water falls as rain or snow in the Upper Colorado River Basin. (An acre-foot is enough to cover an acre with one foot of water.) From measurements of the water that ends up as stream flow, it is estimated that about 78 million acre-feet must be lost by evapo-

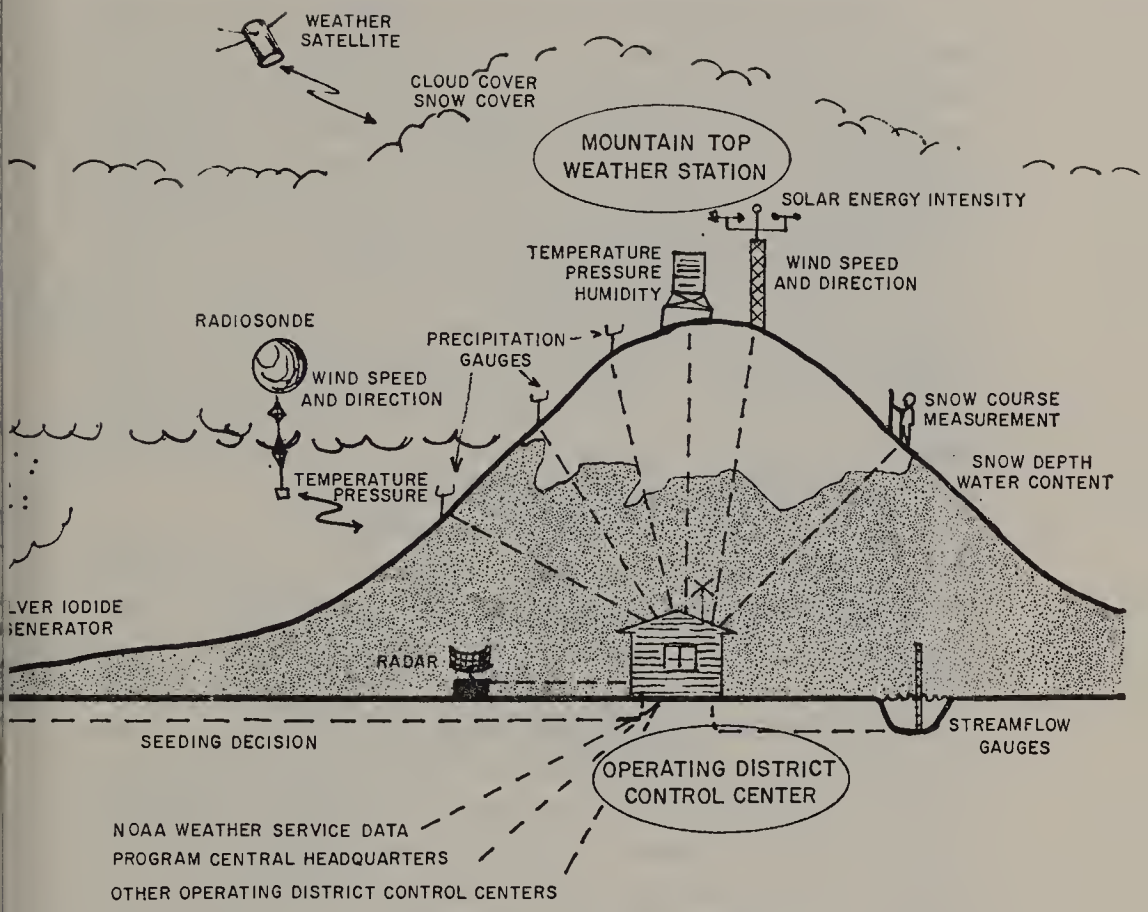


Fig.6. Proposed WOSA Information and control system

ration from the land surface or vegetation. Much of the moisture in the winter snowpack is lost through evaporation from the surface of the snowpack. If the snow is deeper but covers the same area, evaporation will not increase significantly. A heavy snowpack may stay on the ground for a few weeks longer in the springtime when the evaporation losses are high, but overall, a heavy snowpack loses a smaller proportion by evaporation than a light snowpack.

The runoff from the snowpack occurs mainly during the late spring and early summer. As the air starts to warm up, melting begins at the lower elevations and progresses up the mountains. These conditions tend to produce a more or less constant melting during the runoff period. However, unusually warm periods or strong warm winds can cause rapid melting up to very high elevations. These high melting periods can speed evaporation losses, but they also cause rapid increases in stream flow and longer periods of high water flows in streams. WOSA would not influence how often unseasonably early hot spells might occur, but by increasing the snowpack depth and the length of time snow could be on the ground, WOSA would increase the probability of rapid meltoff situations.

The water yield is the runoff that results from the seasonal snowfall. This figure averages the losses throughout the season from the snowpack and during the snowmelt season, as well as the variations from one part of the basin to another. We can only estimate water yield, because there are few measurements of the snowfall at high altitudes. We estimate that in an average year in which cloud-seeding has been conducted at every opportunity, about 48% of the augmented winter season precipitation would reach the streams. If snowfall were a third higher than average, the augmented runoff yield would be 52%, but if it were a third lower than the average, the augmented yield would be 45% (Figure 7).

These yields were used to compute the addition to water supply that a full-scale WOSA could produce. In an average year, 2.3 million acre-feet could be produced within the Upper Colorado River Basin. One year out of three, it might be either lower than 1.1 or higher than 3.6 million acre-feet. Because of the snow that WOSA brings to mountain slopes where the runoff flows out of the basin, about 1.2 million acre-feet of additional water would be produced outside the Upper Colorado River Basin, mostly east of the Continental Divide.

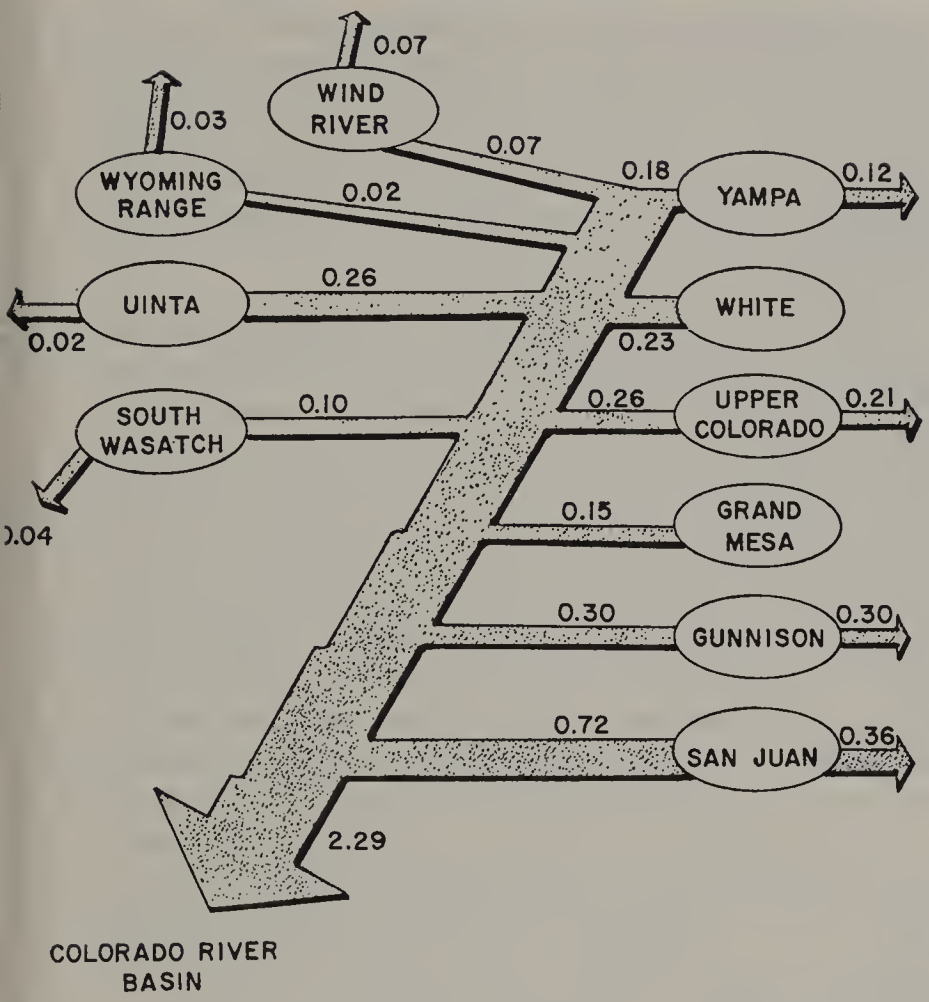


Fig. 7. Possible augmented runoff from the target areas in average snowfall year (Million-Acre-Feet). Total out-of-basin augmented runoff is 1.15 million-acre-feet.

Water Quality in the Southwest

In the Colorado River Basin, water quality is a more urgent problem than projected shortages. The water flowing out of the Upper Basin already exceeds the U.S. Public Health Service Drinking Water Standards for the concentration of dissolved

salts. By the time the water reaches the Imperial and Coachella valleys of California, it is so salty that it damages some crops such as lettuce, celery, and green beans. The salinity of the Colorado River water supplied to Mexico has long been a problem affecting the relations between the two countries. If WOSA could improve the quality of the river water significantly, it would be a great boon to the entire basin.

If the additional water produced by WOSA reached the river without touching the ground, it would dilute the water supply of the river with high purity snowmelt water. However, much of the dissolved salts in the river come from natural deposits of soluble salts that are picked up by streams and ground water. These natural sources contribute about 58% of the dissolved salt in the river flow from the Upper Basin, and water added by WOSA would also pick up natural salts. About 42% of the salt level is accumulated from irrigated agricultural development. In recent years the concentration of dissolved salts in the Colorado River at Lee Ferry, Arizona—the arbitrary dividing point between the Upper and Lower Basins of the Colorado River—has been around 600 parts per million. In an average year, the water from WOSA would decrease this value by only 40 parts per million. This is only about half the improvement that would occur if the river were diluted by the same amount of pure water. If the WOSA waters were used for irrigation in the Upper Basin, or for some other highly polluting use, the quality might suffer more than if there were no augmentation.

The Cost of a Full-Scale WOSA Program

Cloud-seeding decisions must be made separately for each of the ten target areas. For each target area, an organization of men and equipment would be needed to operate, control, and maintain the cloud-seeding activities. To allow cloud-seeding decisions to be made either locally or by a central headquarters these organizations, or "operating districts," should be tied by

radio communication links to a central headquarters and to each other. The central headquarters would handle the management functions necessary to support the activities of all of the operating districts.

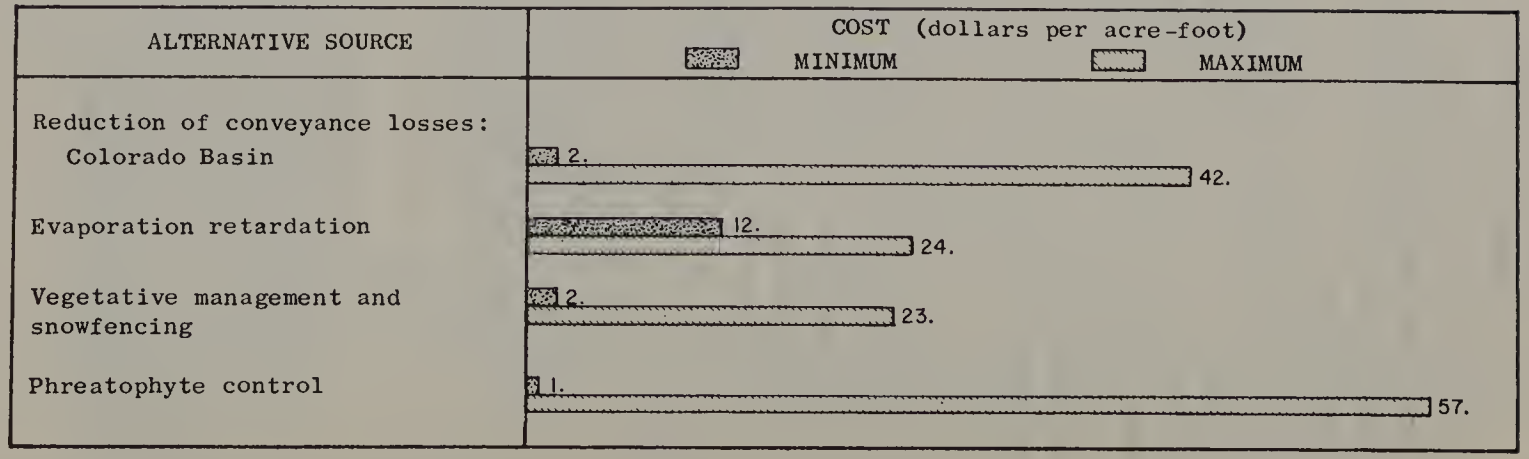
Based upon the actual experience of the Bureau of Reclamation's "Colorado River Basin Pilot Project," we have determined the men and equipment necessary for cloud-seeding, operational control, and equipment maintenance in each target area. From engineering experience, we have determined the spare parts and supplies required for each district. From the expected hours of seeding conditions in each district, we have computed the seeding supplies necessary. We have also determined the staffing and equipment required by the central headquarters. Based upon some known and some estimated costs for all of these items in 1971, we have developed a yearly cost estimate of $5.4 million for the cloud-seeding operations in the Upper Basin. This includes amortization of the investment costs based upon an expected 10-year operating life.

The cost of producing water is the yearly cost of cloud-seeding operations divided by the amount of water produced. We can calculate several different costs:

> The yearly cost for producing 2.3 million acre-feet in the Upper Colorado River Basin would be $5.4 million. The cost of this water would be $2.4 per acre-foot.
>
> The yearly cost of producing 3.4 million acre-feet both within and outside of the Upper Colorado River Basin would still be $5.4 million. However, the cost of this water would be $1.6 per acre-foot.
>
> If four of the least-productive target areas were removed from the system, and only 2.7 million acre-feet of water were added both within and outside of the Upper Colorado River Basin, the cost could be as low as $1.4 per acre-foot.

These costs are significantly cheaper than those estimated for any other known method of augmenting the water supply of the Colorado River (Figure 8).

Fig. 8. Alternative technologies for Colorado River water supply augmentation.



TECHNOLOGY	COST (dollar per acre-foot)	POTENTIAL LOCATION OF APPLICATION
Desalination Nuclear	75.6*	Southern California Coastal Region, Gulf of California, Salt Lake City, Utah
Geothermal	32.6†	Imperial Valley, California
Wastewater reclamation	65.2‡	Metropolitan Areas
Transbasin diversion California State Water Project	65.	Southern California Coastal Region Municipal and Industrial Use
Second Owens Valley Aqueduct	30.	
Colorado River	25.	
Columbia River	70.	

* Based on 1980 public financing, 1968-69 labor costs, 1 million acre-feet per year plant capacity, 4,000 MW net power production.

† Assumes power sold at 3.6 mills/kwh.

‡ Incremental cost over the cost of secondary treatment, 30 million gallon/day plant capacity suitable for direct hauman consumption.

Controlling Avalanche and Flood Hazards

The obvious hazards from too much snow in the Upper Basin are avalanches and floods. To reduce these hazards by reducing either the probability of occurrence or the people or property at risk would add to the cost of water.

In the avalanches or snow slides that have made history, a large mass of snow—tens of acres several feet deep—slips suddenly down a steep mountainside, crushing trees, moving boulders, covering roads, and destroying dwellings. However, not all avalanches are dramatic; some are only small snow slides, and others occur in remote wilderness areas beyond human notice.

Fifteen people were killed in avalanches in Colorado from 1960 to 1965. The greatest potential avalanche hazard is to the highway traveler, since more and more people drive to ski resorts. Also, more and more hunters, cross-country skiers, and snowmobilers are entering the more remote mountainous regions.

Cloud-seeding makes it snow longer, rather than more often. The effect of seeding is to increase the total new snow during storms. An increase in snow depth leads to an increased probability of an avalanche.

There are four basic methods available for controlling avalanche hazards:

Not permitting people or property in avalanche terrain when the avalanche probability is high.

Stabilizing the snow (packing it down by skiing or trampling, or breaking up snow slabs by blasting).

Installing passive devices such as wind panels for redirecting snowladen wind; mounds, nets, or walls to halt the motion of the snow avalanches; and avalanche sheds to carry the snow slides over highways or railroads (Figure 9).

Controlling cloud-seeding to minimize the hazard.

AVALANCHE SHED THAT CARRIES AVALANCHE RUN OVER HIGHWAY

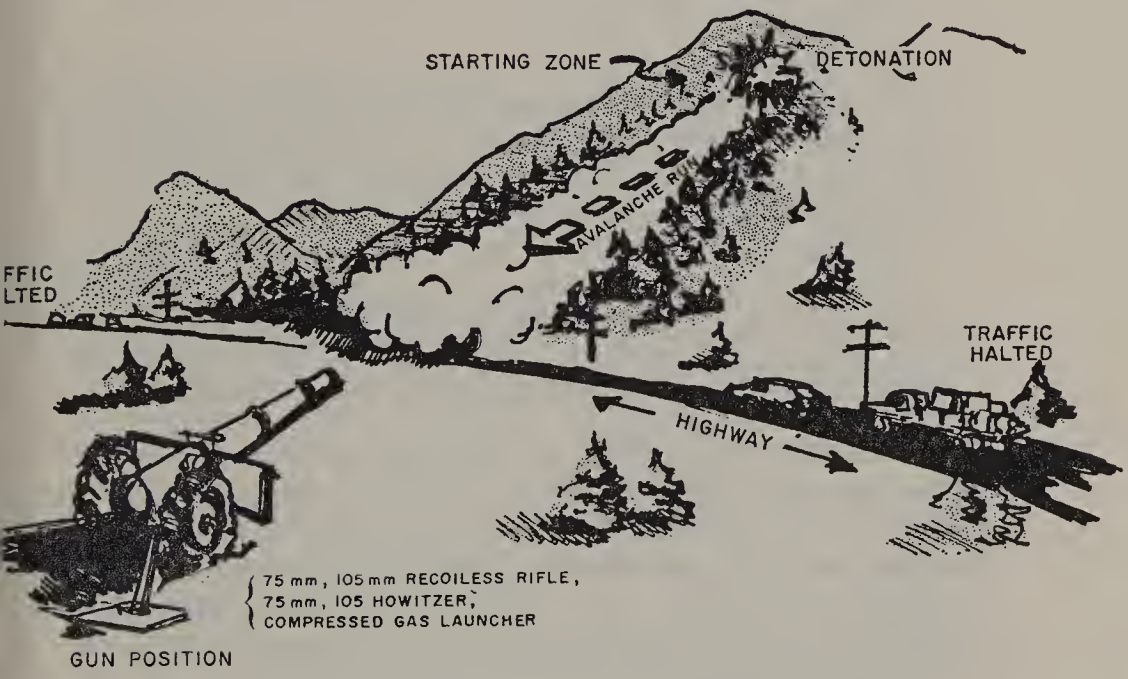


Fig. 9. Methods of avalanche control

The natural level of avalanche risk is accepted by residents as part of life in the region. A program that combines all of the possible control procedures could hold the risk below the natural level, even with WOSA, at a relatively small cost. With such a program:

Roads should be closed on the worst storm days. Such days occur naturally two to three times in an average winter in the Ouray-Silverton area of Colorado, for example, and with WOSA the roads might be closed on five days in an average winter. The costs are inconvenience to travelers and to workers in the area, and loss of revenue to local business and industry.

Passive control structures should be built at the small number of runs where avalanches are extremely frequent. One control structure should be built (at an estimated cost of $150,000) at Blue Point, near Silverton, Colorado. It would be desirable to build at least one more structure along the Ouray-Silverton road for a cost of $500,000.

Active avalanche control should be extended to provide for all the expected increases brought about by WOSA, and also to provide control on nonpublic roads. The expected increases in cost would be $24,000 per year in Colorado and less than $10,000 per year in Wyoming.

Cloud-seeding should be limited so that the seasonal snowfall does not exceed that of high years such as 1957, 1962, and 1965. If this were done, no new avalanche runs should result from the WOSA program, but average WOSA water production would be reduced by about 10% in those years.

Flooding occurs when a stream channel cannot hold the volume of water flowing into it. A summer cloudburst can cause flooding, and so can an early thaw, or a warm spring rain. High temperatures or warm winds can happen at any time during the snowmelt season. They are unrelated to the amount of snow on the ground, so that flooding has occurred in years of light snowpack as well as heavy.

WOSA will increase the amount of runoff water to be handled by the streams. If the snowmelt season lasts as long as

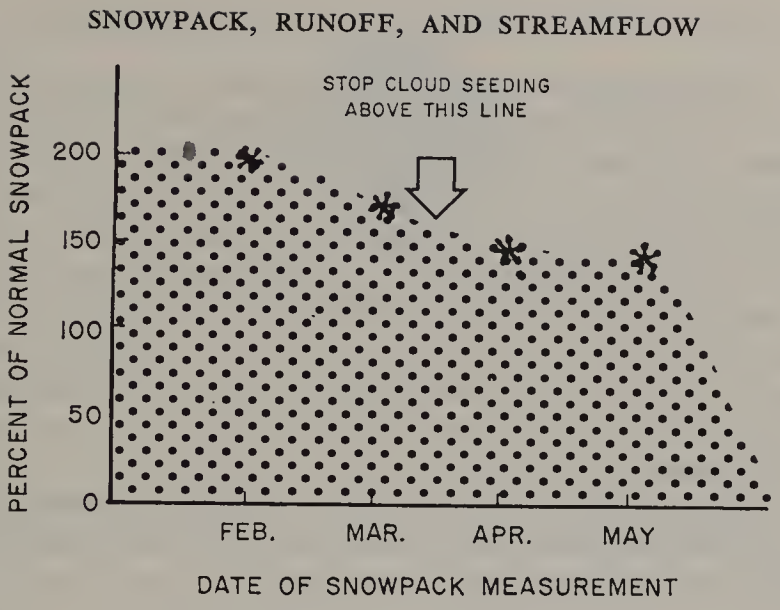


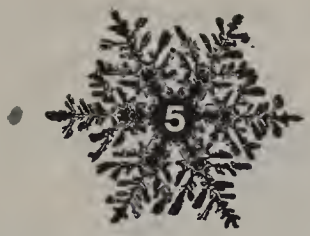
Fig. 10. Seeding limits for flood control

it did before WOSA, more water must be handled by the streams in the same time. If the snowmelt season is a few weeks longer because of WOSA, the possibility of a high temperature or warm wind is increased. Thus, WOSA will increase the probability of flooding.

The natural stream channels in the Upper Basin can generally handle more water than the average seasonal snowpack yields. By comparing historical flooding records with snowpack accumulations, we can determine how large a runoff the streams can handle. This has been done for the target area of the Colorado River Basin Pilot Project in the San Juan Mountains. The results show that if the accumulated snowpack can be held to 150% of the average on April 1, the probability of more than minor flood damage will increase only slightly. WOSA could stay within these limits and reduce the WOSA-created precipitation by only about 10%. This is the same limitation that would be desired to reduce the probability of creating new avalanche runs (Figure 10).

Flood damage can be reduced by effective forecasting and flood warning that gives people time to prepare. The weather, climate, precipitation, snowpack and streamflow information needed for proper evaluation and control of the WOSA program are the same kinds of information needed for flood forecasting and warning. The WOSA program could provide flood warning and forecasting at little additional cost. With adequate forecasting and warning, the average saving in flood damages would more than offset any losses resulting from the WOSA program if it observed the precipitation limits for flood and avalanche hazard control.

Flooding in the Lower Basin due to snowmelt runoff in the Upper Basin is virtually impossible because of the vast storage capacity in Lake Powell and Lake Mead.



Environmental Effects

About 1930, the Upper Colorado River Basin began to enter a dry period. If it continues WOSA could raise the average river flow to near that of its recorded history (1896–present). The variation in precipitation from one year to the next is much greater than the shift WOSA will bring, but over many years WOSA will affect the plants and animals of the Upper Basin, however slightly.

Effects on Animal Life

Identifying subtle long-term effects in biological communities that face very different environmental stresses from one year to the next is difficult. Even if long-term changes can be identified, long-term cyclic changes in the weather occur naturally, and would be expected in the future. If we cannot predict precise environmental effects for WOSA, at least we can describe the natural environmental stresses caused by winter snow and show how WOSA might influence them.

Changes in the temperature and the amount of moisture available will encourage some kinds of vegetation and discourage others. In turn, changes in vegetation will encourage some kinds of wildlife and discourage others. With the long-term average increase in snowfall that WOSA will bring, we can expect a gradual shift of plants to lower elevation. We will see the timberline retreat to lower elevations over a period of many years. Mountain sheep and goats that winter in the tundra

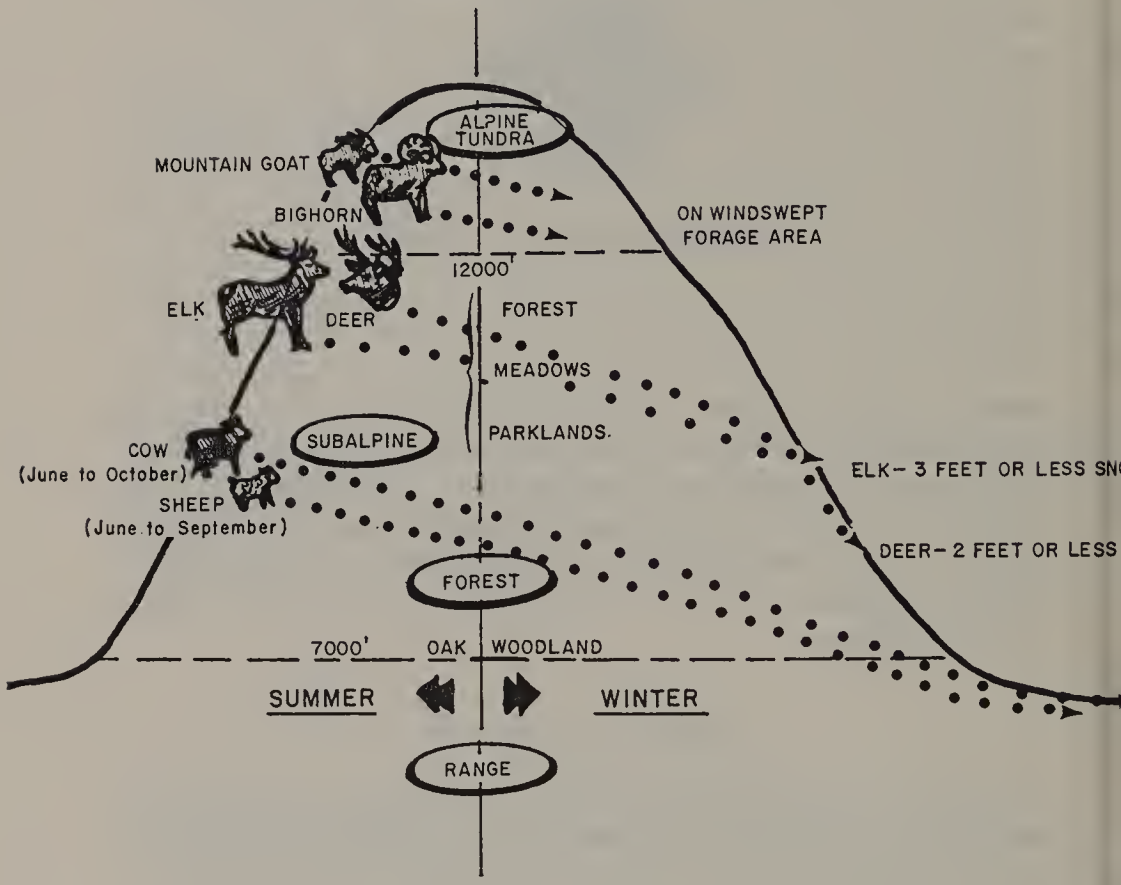


Fig. 11. Vegetation regimes and animals that depend upon it for grazing and browsing

above the timberline need windswept areas where enough of the snow is blown off to allow them to forage for food. More snow at high elevations may mean fewer good foraging areas.

The forest ranges from timberline down to about 7000 feet. By increasing the moisture available, WOSA will prolong the growing season for forage plants upon which big game (deer and elk) as well as livestock (sheep and cattle) depend for spring, summer, and fall food. If deep snow accumulates earlier

in the fall or lasts longer in the spring, these animals will be forced to remain longer on winter ranges at lower elevations. Winter ranges are generally much smaller than summer ranges (Figure 11), and there is keen competition among game animals and between big game and livestock. As a result, the length of time which elk and deer are forced to spend on winter ranges affects the numbers that survive from year to year. Livestock can be shipped to better pasture during the winter, or given supplemental feed to carry them through.

The whole ecological system will eventually become involved if the basic food input, vegetation, is disturbed. The species of mammals, birds, and insects that depend upon a food source will reflect changes in the abundance of that food source. In turn, the predators for these vegetarian species will also be affected. Eventually, nature's scavengers, those life forms that feed upon carrion or are responsible for the decomposition of organic matter, will also respond to the changes. Even the character and formations of the soil will in time be altered by a change in the kind of vegetation growing on it.

Effects on Streams and Lakes

A layer of snow on the ice cover of mountain lakes prevents the sunlight from penetrating to the plants in the water. Plants need light in order to carry on the growth process, photosynthesis, in which they transform carbon dioxide into oxygen. At the same time, decaying organic matter is consuming what little oxygen is dissolved in the water. If plants can't get enough light to make oxygen, the dissolved oxygen may become so depleted that the fish, insects, and other aquatic animals perish. Increasing the snow cover on lakes would tend to increase the number of mountain lakes that have such a winter kill and also the frequency with which it occurs. The same kind of winter kill can happen in streams that freeze over, but often a snow blanket on a stream acts as insulation that prevents it from freezing solid.

Snowbanks sometimes collapse into streams that do not

freeze over, smothering fish and damming the channel so that water cannot get downstream. This exposes downstream fish, fish eggs, and aquatic animals to suffocation and freezing. Anchor ice also can damage stream life forms. Anchor ice is a spongy mass of ice crystals that forms on stream beds during cold clear nights in water that is not frozen over. The sun melts anchor ice just enough to detach it and it carries away life forms that dwell on the stream bottom. Snow accumulations might help to prevent damage from anchor ice.

The high mountain streams are fed mainly by snow, so that they run fullest in mid-spring. WOSA would extend the period of high meltwater runoff into late spring or early summer, and shorten the period of low flows. Flows would also be higher during the snowmelt season. The effects of WOSA on aquatic lifeforms would be potentially more severe in the headwater streams, because the effect on flows is greatest there.

The high spring stream flows tend to wash things downstream, such as algae, silt, aquatic insects, young fish, and fish eggs. These life forms are carried downstream to locations that may be less suitable for their survival.

In addition, the greater the volume of water moving downstream at any one time, the greater the scouring action on the stream bed. Loose material needed by aquatic insects for shelter, or by egglayers to anchor their egg masses may be swept away. WOSA could also lower the average water temperature in the high mountain headwater streams and high mountain lakes. Differences of only a few degrees may alter the distribution of the various life forms within a stream. The breeding seasons, the ability to complete a normal life cycle, the rate of growth, and ability to develop to normal maturity may all be affected.

High inflows and outflows of meltwater tend to replace the surface layers of lakes with water that is poor in the nutrients needed by aquatic plants. This can affect the production of adequate aquatic food organisms later in the year.

On the average, WOSA would result in generally wetter conditions that exist for longer periods in the mountains. More

mosquitos can be expected, as well as more ticks, and other insects. Mosquitos, ticks, and flies spread disease, so that increases in their numbers could contribute to a higher incidence of disease.

Silver Iodide in the Environment

A full-scale WOSA program in the Upper Colorado River Basin will use, on the average, an estimated 8,000 pounds of silver iodide per winter season. All of this is released to the atmosphere in the form of a smoke that is widely dispersed by the winds.

Silver iodide dissolves only to a very minute extent in water. It decomposes in sunlight to form metallic silver and elemental iodine. Iodine can be a hazard if the concentrations are high enough. The iodine vapor concentration in the air around the silver iodide generators, where it would be expected to be highest, is estimated to be below the accepted safe level for humans. However, we don't know what the long-term levels of both silver and iodine might be in these areas, or how continued exposure to them might affect plants and animals.

Harmful effects in living things can result only from soluble forms of silver (silver ions). Even though both metallic silver and silver iodide are extremely insoluble in water, soluble organic forms of silver might develop as a result of biological processes in the bottom muds of lakes, streams, and reservoirs, as it does for mercury. At present no soluble organic forms of silver are known to occur in nature at the normal water temperatures of lakes, streams, and reservoirs.

Some materials that are present in water in low concentrations can build up to dangerous levels in moving up through the food chain. A single-cell organism may metabolize silver rather than being killed by it. A kind of insect feeding mostly on that organism would absorb the metabolized silver, and fish that feed on that insect might have a high level of silver in their flesh. This is how the mercury level can become dangerously high in tuna or swordfish, for example. It is known that a num-

ber of marine life forms concentrate silver or iodine. Whether the highest levels found in these marine life forms impair their well-being, or the well-being of their predators, is not known.

The life forms most susceptible to soluble forms of silver are microorganisms, invertebrates, and fish. Microscopic life forms are vital in the fixation of nitrogen in soils, and in the digestion of food by cattle, sheep, deer, and elk. Invertebrate life forms such as insects are important food sources for certain fish, for some birds, and for some other animals. Fish are food for other fish, for fish-eating birds and animals, and for people.

There are uncertainties in our knowledge of:

The distribution in the environment of silver iodide from cloud-seeding

The rate of decomposition of silver iodide in sunlight

The biochemical transformation of silver and silver iodide into soluble forms of silver

The biological magnification of silver and iodine in the food chain

The toxicity of soluble forms of silver to these various life forms. These uncertainties can all be reduced with additional research and field experiments

With the current state of knowledge, we have no reason to believe that silver iodide will present an ecological problem, but we cannot be certain that it won't.

Minimizing Environmental Damage

WOSA may produce long-term environmental changes, but we don't know enough to predict how great or how extensive they might be. No major changes are likely to result directly from the kinds of snowfall, climate, and water-related conditions that WOSA will create. However, unforeseen changes may result from the accumulation and interaction of many minor or indirect effects. Even if we could foresee such changes, we don't

know how they might affect human activities, or whether anyone would even care.

We will have the capability to modify the weather on a regular basis over widespread areas long before we could have a detailed understanding of its possible environmental and ecological effects. We think that an operational WOSA program in the Upper Colorado River Basin could be environmentally safe, if the environmental and ecological effects were adequately monitored and evaluated. Monitoring would add to the cost of the program, but it would also allow us to enjoy the benefits a WOSA program could provide and to deal with problems as they become apparent, instead of foregoing the benefits or pretending there won't be any problems.

Economic Effects of an Augmented Snowpack in the Upper Basin

THE HIGH mountain areas that will receive significant amounts of additional snow are mostly National Forest land interspersed with a number of isolated towns. Lead, zinc, gold, silver, and molybdenum are mined in the mountains; the Englemann spruce, which grows at high altitudes, is the most important timber source in Colorado; high meadows are used as summer pasture; skiers, hunters, fishermen, hikers, and tourists all visit the mountains; some towns also serve passing travelers. All of these activities take place under natural snowfall conditions that vary greatly from storm to storm and from year to year. WOSA will tend to create more heavy snowfall days and more winters of heavy snowpack. The economic effect of WOSA could be severe for those activities that depend for their profitability on years of light snowfall.

The Effects of More Snow

WOSA would be expected to affect mining in the Colorado Mineral Belt, both because of the greater seasonal accumulation of snow and the heavier snowfall from individual storms. Mineral prospecting will be curtailed by a longer period of snowcover. Mines worked only in summer may have a shorter season. Extra snowpack may increase the risk of mine flooding. For mines that are operated year-round, snow removal costs for above-ground facilities will increase. In the San Juan mountains, miners lose 5–6 days of work per year because snow closes

the roads. With WOSA, they could be expected to lose an additional 3 days per year. The mineral losses could be made up by overtime work, but cost to the mining operation will be higher.

Most of the timber logged in the target area is on National Forest land. The timber areas to be cut are appraised, advertised, and sold at auction by the Forest Service of the U.S. Department of Agriculture. In appraising the standing timber, the Forest Service considers market price and operating cost so that the timber operator can make a fair profit. The operating cost allowance is re-evaluated every six months based on detailed (and confidential) cost data from the operators. If WOSA increases operating costs, the appraisal values will be lowered, so that the effect of WOSA on the cost of logging is eventually absorbed by the Federal government.

More snow benefits skiing only if it allows a longer season. WOSA could lead to a good snow base for skiing as much as 3 weeks early. If this made Christmas skiing possible, WOSA would prevent a disastrous year; it if made Thanksgiving skiing possible, the season could be highly profitable for the ski operators.

Hunting, fishing, and summer recreation depend on the length of the season between the disappearance of the snowpack in the spring and the onset of snowstorms in the fall. However, family camping and similar recreation activities are tied to the summer vacation period, which seems to be safely within the snow-free period, even with WOSA.

Sheepmen and cattlemen lease government lands in the target areas for summer pasture. The animals winter in sheltered valleys and are taken to higher pastures by degrees as the earlier grasses in the lower pastures are grazed over. Much of the lowland pasture is irrigated. The higher average snowpack of WOSA will increase the runoff and improve the lowland pastures, permitting prolonged grazing at lower elevations. The prospect of more and better grass in lowland pastures should more than offset any loss due to the shorter summer pasture season in the high mountains.

The economic impact of WOSA on transportation falls into several categories. An increase in snowfall hours will raise yearly snow removal and ice control costs, increase traffic delays and travel time, and make highway accidents more probable. WOSA will not affect high-altitude military or commercial air operations over the target area, since clouds suitable for seeding are well below altitudes that would interfere with flight operations. Falling snow will affect local landings and take-offs by reducing visibility at the few airports in the target area. (Most airports depend on county or city road crews for snow removal once the snow has fallen.)

Water Requirements

Throughout the western United States, all sorts of projects are in various stages of development—feasibility analysis, planning, construction, and operation—to move water from where it is available to locations where it is "needed" for municipal, industrial, and agricultural uses. It takes many years to carry a water supply project from the drawing board to the irrigation ditches. Water needs, therefore, are necessarily based upon some kind of projection of the future. However, even the most reasonable projections often become a self-fulfilling prophecy. If we are planning water projects for Los Angeles for the year 2000, for example, we may take the projected growth rate, multiply by present water use per person, and come up with an estimate. Then we begin planning facilities to get that water to Los Angeles in time. If Los Angeles doesn't run out of air or power first, it may grow to require the amount of water that was projected.

In the arid west, irrigated agriculture consumes most of the available water supply. Expansion of agriculture depends almost completely upon the availability of water. Therefore, the future water needs for agriculture are largely determined by the policies that make water available in a given location. In some areas, agriculture has become established because of an existing

supply of ground water. Where ground water is used faster than it can be replenished, the farmers must drill increasingly deeper wells. At some point, the cost of pumping eats away the profit on their crops, and they "need" surface water supply projects. Other projects are urged because land is available that could grow some kind of crop if irrigated. However, most of the land that has not yet been irrigated is good only for feed grains for livestock.

No one today is short of water in the Colorado River Basin. If we could freeze the situation at the present level of development, we could forget about future shortages. However, there are many pressures for development:

There is land in the Upper Basin that could be irrigated to grow feed grains for livestock.

There are vast oil shale deposits in Colorado and Wyoming that could be mined and processed to yield petroleum products, although they are not currently economical.

There are large coal deposits in the Four Corners region of Colorado, Utah, Arizona, and New Mexico that could be strip mined. These deposits could fuel huge electrical power generating plants that supply the large metropolitan areas of the Southwest, they could provide a source of low sulfur coal for generating electrical power throughout the country, and they could be used to manufacture synthetic natural gas. (Some strip mining has already begun.)

There are growing urban areas and agricultural areas in eastern Colorado, southeastern Wyoming, central Utah, and central New Mexico that are becoming dependent on water supplies from the Upper Basin.

There are agricultural and urban areas in central Arizona that are dependent upon a ground water supply with a falling water level.

The extent of future water shortages in the basin depend upon two factors: the existing supply, and the claims that can be made upon it by these pressures for development.

A reasonable estimate of the existing average Colorado River water supply is 13.8 million acre-feet per year. This is the amount that would flow out of the Upper Basin into the Lower Basin if man took nothing out. Almost no water flows out of the Colorado River into the Gulf of California. Evaporation (and other losses) and man's uses account for about 12 million acre-feet per year. Of this amount around 3 million acre-feet disappears from the Upper Basin. The difference between the natural supply (13.8 million acre-feet) and the depletion (12 million acre-feet) of around 1.8 million acre-feet per year is filling Colorado River Basin Reservoirs. The usable capacity of the major reservoirs—some 60 million acre-feet—is a little over half-filled.

The allocation of the Colorado River water supply implied by the Compact of 1922 and the Mexican Treaty would seem to call for a minimum average annual stream flow of 17.5 million acre-feet. However, large reservoirs are necessary to stabilize the flow and regulate the water diversions in order that these allocations can be used. Large evaporation losses from the surfaces of these reservoirs can be expected in addition to other natural losses. Accordingly, at least 19 million acre-feet is necessary each year to satisfy this allocation.

If all authorized projects were constructed, California would have to give up 0.7 million acre-feet per year now being used, and the Colorado River water supply would have to be augmented to satisfy the Mexican Water Treaty. California is already augmenting its south coastal supply from other sources. However, if each state is to receive its full entitlement, the water supply will have to be increased. To build the authorized projects, Congress would have to appropriate large sums of money. Upper Basin water use would have to increase sharply before all the states of the basin would need their full entitlement. The only development that could bring this about is extensive exploitation of Upper Basin coal and oil shale mineral resources. WOSA would be needed in a very few years if Congress appropriated the money for the authorized projects and thereby

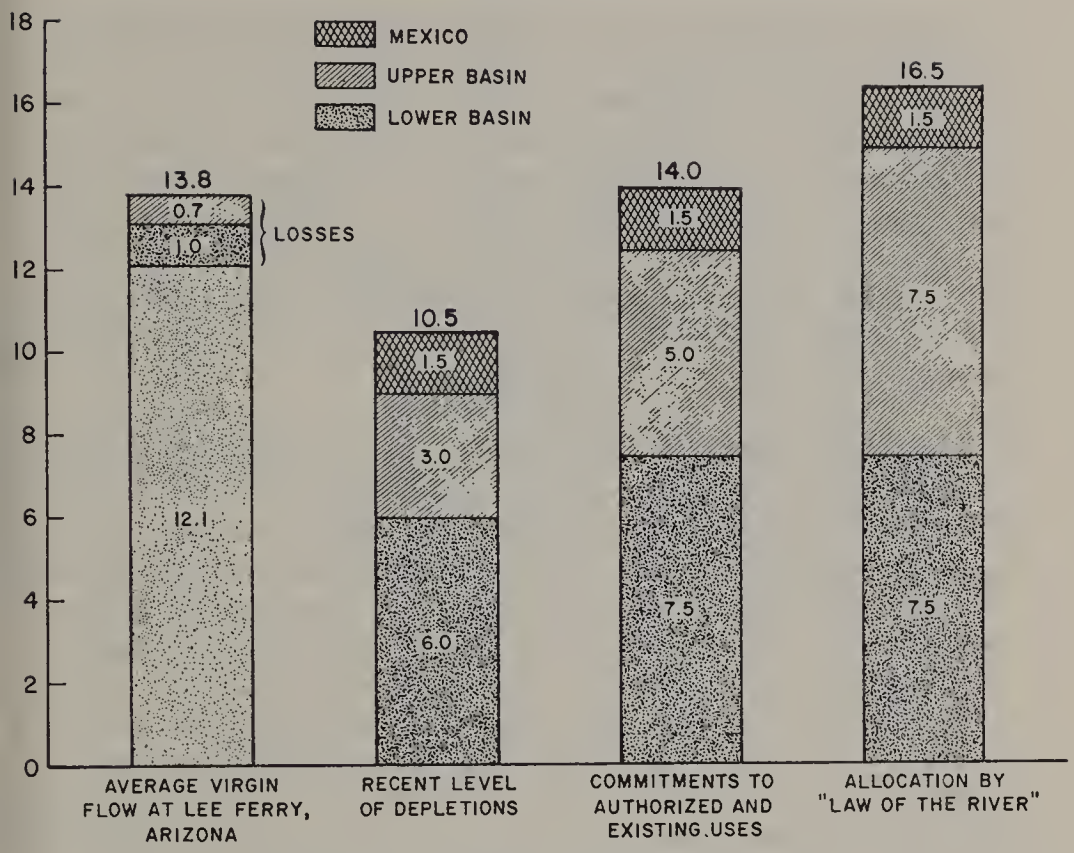


Fig. 12 Colorado River water supply

created water shortages. The slow rate of economic development that would be expected in the Upper Basin would not create water shortages for a great many years (Figure 12).

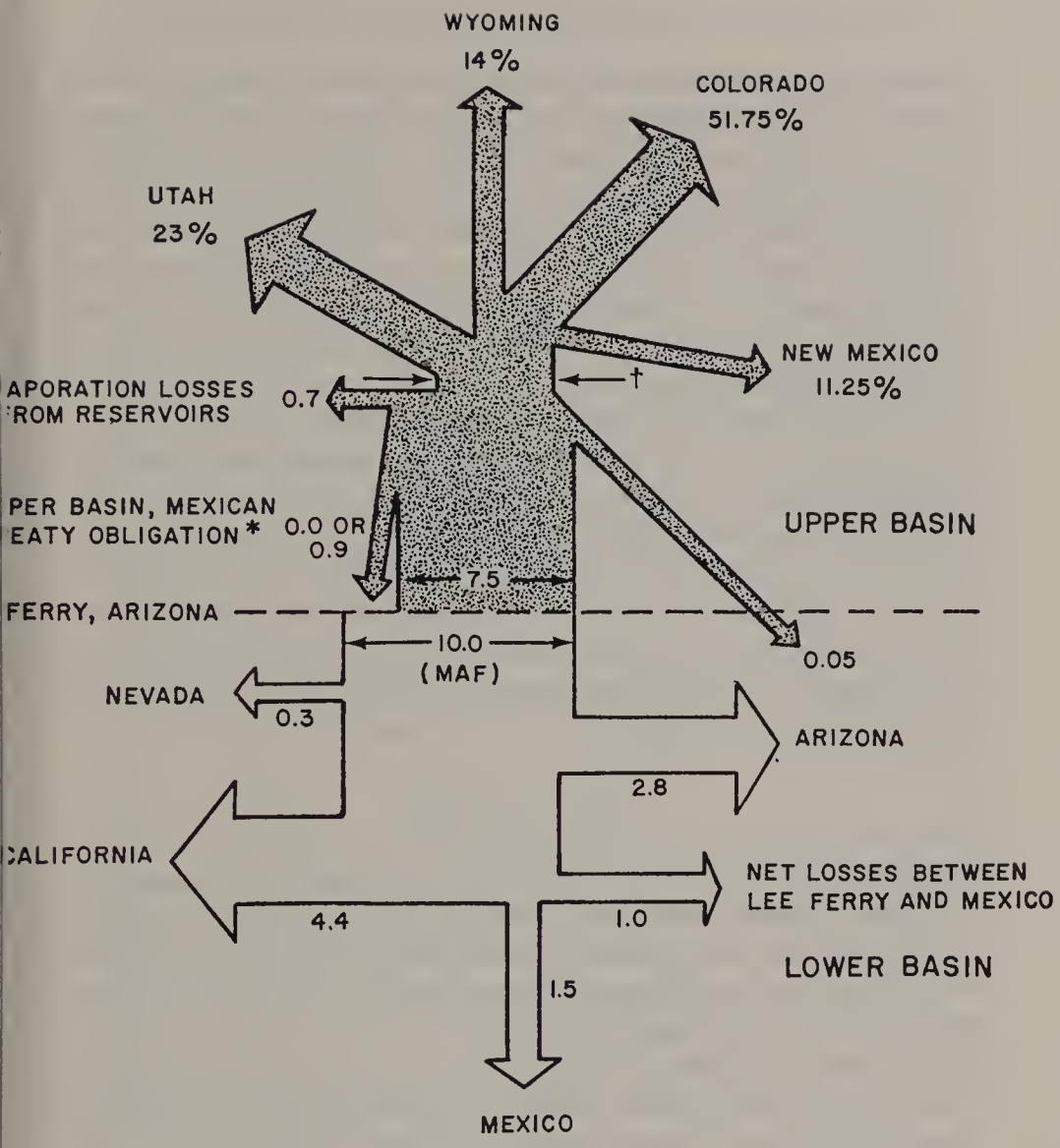
WOSA Water—A Question of Ownership

The allocation of the water supply of the Colorado River has been the subject of long and bitter disputes among the states through which it flows. The history of agreements, legislation,

court cases, and treaties that have dealt with this problem is known by the legal profession as the "Law of the River." The Law of the River has settled many issues, but many others remain unresolved. The problem of ownership or allocation of WOSA-created water is not settled, but the Law of the River does state who has the power to settle it and what claims could be put upon it. How this question would ultimately be resolved to a great extent determines the opportunities that would exist for dealing with many problems that an operational WOSA program would create (see Figure 13).

The first division of the Colorado River water was by Interstate Compact in 1922. This compact divided the waters between an Upper Basin and a Lower Basin. The second division was made by Congress in the Boulder Canyon Project Act of 1928. This act divided the Lower Basin portion among the three Lower Basin States—California, Arizona, and Nevada—even though at the time Congress was not sure that it had the power to do so. The problem that Congress was trying to solve was the refusal of Arizona to ratify the 1922 Interstate Compact and to join in a Lower Basin interstate compact. It was necessary to settle the matter of how much water belonged to Arizona before Congress could authorize the building of projects on the river to use water in Arizona. At the time it was thought that the only way to finally settle Arizona's portion was litigation before the Supreme Court. In 1952 Arizona vs. California was initiated. The opinion of the Court was finally rendered in 1963 and in 1964 the Court issued its decree. The Supreme Court found that the powers of both the division of waters between states and the allocation of water within a state did in fact belong to the Congress. This was more power than Congress thought it had under the Constitution. But finally Congress could get on with authorizing projects to develop the water resources of the Colorado River.

In 1968 Congress enacted the Colorado River Basin Project Act—Public Law 90–537. This legislation authorized the Central Arizona Project and specified water priorities by guar-



The obligation of the Upper Basin to the Mexican Treaty is disputed.

Difference available to be divided among Upper Basin states according to percentages given. If the virgin flow of the river is 14 maf and the Upper Basin is subject to the Mexican Treaty obligation, then the amount available for use in Upper Basin is 4.9 million-acre-feet.

Fig. 13. Allocation of Colorado River water supply according to "Law of the River" (Million-Acre-Feet)

anteeing a minimum allocation to California. Shortages in the water allocation were to be borne first by the Central Arizona Project. Congress also declared in the legislation that it recognized a future need to augment the water supply of the river. It stated that when the river is augmented, the obligation of a treaty to supply Colorado River water to Mexico that was agreed upon in 1944 would take the first priority. It also stated that the costs of satisfying the Mexican obligation would be borne by the federal government.

There is reason to believe that an operational WOSA program in the Upper Colorado River Basin would not satisfy the conditions that Congress may have had in mind when it established this augmentation policy for the river. Some sort of specific Congressional action, or legal litigation, would be required to allocate WOSA water to the Mexican Treaty. If the water should be allocated to Mexico, it would foreclose any opportunity for forming an innovative public policy to deal with the problems created by a WOSA program.

Water Benefits

The benefit of water is simply its value to a user. To a man dying of thirst, a gallon of water may be priceless, but a million gallons would not be a million times more valuable. A man who uses water to grow crops is not going to buy that water at a price so high he loses money on his product.

In the arid west, so much water is used in irrigated agriculture that all other water uses could easily be met by transfers from agriculture. Theoretically, if water could be freely exchanged, the farmer would be willing to sell his as soon as he could make more money selling his water than he could by farming. This means that the benefit to the nation cannot be greater than the price the farmer would be willing to pay for water. However, in much of the west, water supplies are not rationed by the price of water in a free market, but by administrative means. Water is made available to irrigators at prices

below the full cost of production and distribution. Therefore, local benefits can be greater than national benefits because of this subsidy.

Before the water can be used, it must be taken out of the river. In arid climates, water must be stored in reservoirs if a year-round supply is to be available. The amount of water that can be stored and distributed with existing dams and aqueducts is limited. If demand for water exceeds the capacity of the storage and distribution system, additional facilities will be required. WOSA water benefits will have one value if only the currently built water resource projects on the river will be used in conjunction with WOSA. The value will be quite different if those projects that have been authorized by the Colorado River Basin Project Act (P.L. 90–537) are built, so that more water can be distributed and used.

At present, not all the water that flows down the River is used. If WOSA is undertaken on a large scale, the added water will flow down the River without being drawn out in either the Upper or Lower Basins. The added water will have three possible benefits: a slight improvement in water quality, an improvement in the reliability of river flow, and increased hydropower generation. The Mexican Treaty obligation will go on being met with leftover water, for which there is no competitive use. The improvement in water quality would allow a yearly saving of $2.5 million in water quality management programs that have been proposed. The hydropower generated by the WOSA water in the generating stations on the river would save a yearly $5.3 million in fuel that would otherwise be burned in older, less efficient steam electric stations. We have not been able to put a value on the improved river flow reliability, but it would probably be small.

The Colorado River Basin Project Act of 1968 (P.L. 90–537) declared the Mexican Treaty to be a national obligation that shall be met by any water augmentation project planned under the Act and authorized by Congress. In addition, the Act authorized the Central Arizona Project and five

projects in the Upper Basin. Congress has not yet authorized *any* augmentation project, but it has appropriated money to begin some of the authorized projects. If the authorized projects were built, they would increase the consumption of the Colorado River water to the point where the WOSA water would be used.

The water to be added by WOSA is roughly equal to the U.S. commitment to Mexico under the Treaty of 1944. If the WOSA water were allocated to Mexico, it would relieve the Basin states of any obligation they have to Mexico under the Colorado River Compact. An equivalent amount of water would therefore become available for the water-short P.L. 90–537 projects. The benefit of WOSA water in this case would be equal to the cost of the cheapest alternative way of providing water to Mexico. Since the cheapest alternative way would be to withhold water from the Imperial Valley, this cost is estimated to equal the benefits foregone by 1.5 million acre-feet per year in agriculture in the Imperial Valley, or some $30 million per year.

A more realistic way of viewing the benefits of WOSA is that augmentation is necessary to make the P.L. 90–537 projects feasible. Then, WOSA creates no new benefits outside those already claimed for the P.L. 90–537 projects. All that it does is to add to the costs, and the costs of the P.L. 90–537 projects already exceed the benefits.

The amount of runoff that will be produced outside the Colorado River Basin by a full-scale WOSA program in the basin is about 1.2 million acre-feet. With the existing facilities, this water would create some $900,000 per year in benefits from hydropower production; $2.0 million per year in benefits from the use of water in agriculture; and $2.1 million per year in benefits from the use of water in urban areas.

Summary

If only existing facilities are used to store and distribute WOSA water and generate power, benefits of at least $7.8 million an-

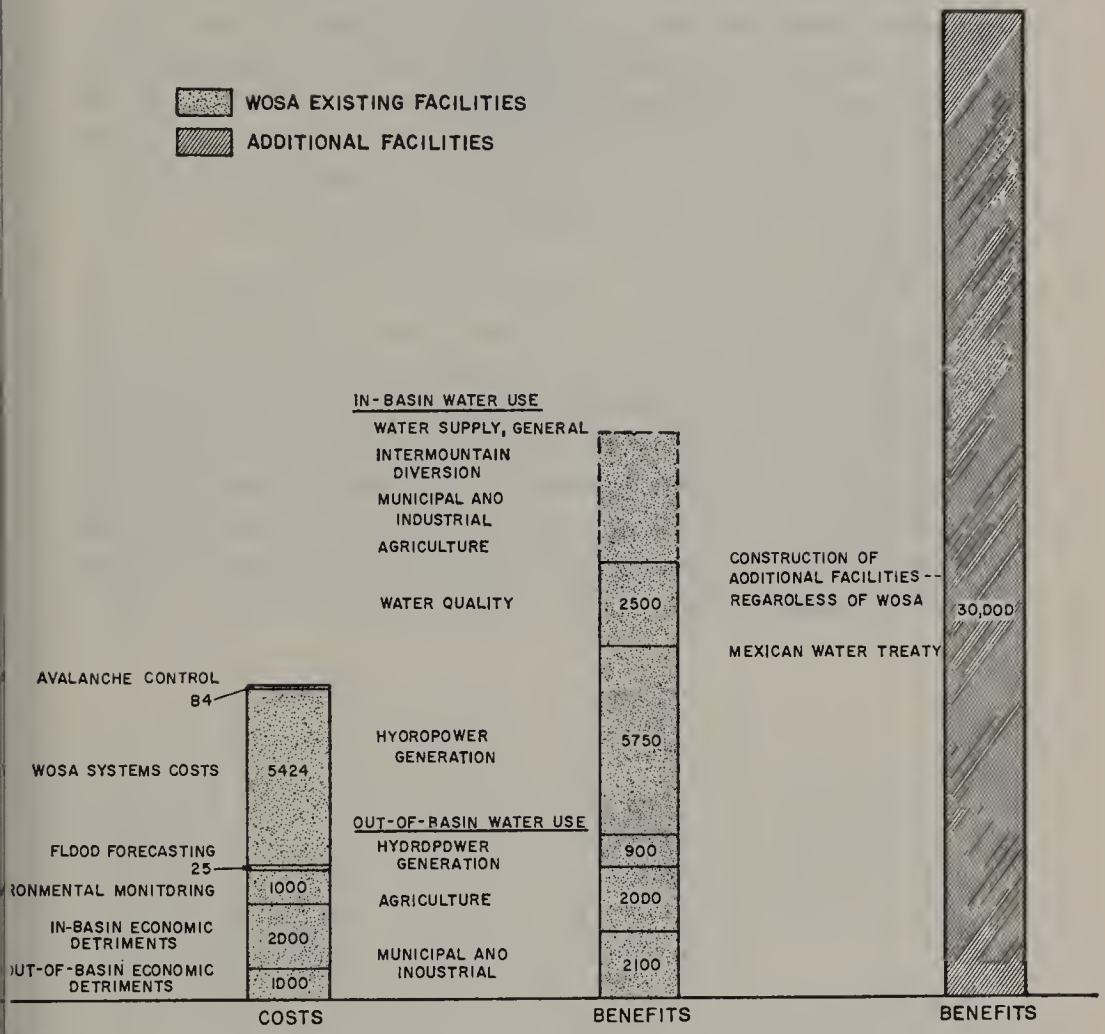


Fig. 14. Costs and benefits (Thousands of Dollars)

nually could be generated within the Colorado River Basin, and $5.0 million annually by the out-of-basin runoff. Of the $12.8 million total annual benefits, $6.2 million is accounted for by electrical power generation.

If Congress appropriates money for P.L. 90–537 projects, a situation could arise where WOSA could "rescue" anticipated

benefits. These have been estimated on the basis of the minimum cost of satisfying the Mexican Treaty, or $30 million per year. If, however, the appropriations decision takes account of the WOSA potential and allocates it to ensure that there is enough water, then the cost of WOSA is added to the P.L. 90–537 project *costs*, but the anticipated project *benefits* remain unchanged.

We have estimated a total annual cost for WOSA of approximately $9.5 million. This combines the direct operating costs for the WOSA program, the costs of an avalanche control and flood forecasting system, and the cost for an environmental monitoring program that includes ecological and human health monitoring as well as monitoring the impacts on social and economic systems. The costs to the target areas from additional snow are also included, since compensation for these impacts could be borne by the WOSA Program (Figure 14).

WOSA and Public Policy

TECHNOLOGY ASSESSMENT will not of itself form public policy, but it will indicate the problems that are likely to arise and the various means that are available for dealing with them. The policy that emerges will result from the decisions that are made by all those who can influence the course of future events. In the final analysis, public policy is what the public does.

Laws, Institutions, and Public Policy

To the extent that they can be, future events are controlled through legislative and institutional means. These means are not independent; each relies upon the other for a full expression as public policy. The standards of the law govern many of our personal and public transactions while institutions are the means through which society accomplishes its business.

The law is constantly being defined for new situations through legislation and the actions of the courts. The law works in a well defined manner that builds upon its past and is directed at remedying the injustice of accomplished actions. The administration of our law is characterized as an institution of justice because it attempts to redress public and private wrongs. It is fundamental to our Anglo-Saxon law and to our freedoms, that the law cannot act to prevent a wrong.

Institutions are created by society to accomplish certain things. They are very flexible in how they are formed and how they work, but once formed they tend to be inflexible in the face

of changing events. They may be established to accomplish things that the law cannot because of the very strict manner in which the law must work. Therefore they are effective means of preventing injustices that the law might otherwise be called upon to remedy after they have occurred.

Weather Modification—A Question of Responsibility

The existing public policy on weather modification deals in a very preliminary manner with two aspects of the same basic question:

Liability for damages resulting from weather modification activities

Regulation of weather modifiers and weather modification operations

As mentioned before, the administration of the law does not prevent damages but rather attempts to redress injured parties after they have been damaged. Therefore when we do something novel and someone feels that he has been damaged by it, the court must look to what is called the "common law" to determine if damages should be awarded. Because the situation is novel, a specific body of laws or statutes is not available to resolve the conflict. Weather modification as a legal claim for damages or relief is not new. Towns have hired rainmakers since the middle of the last century. However, dependable weather modification is new, and has not been reduced to general practice in any of its applications. The common law has limited experience in resolving weather-modification conflicts, and little has been done in establishing responsibility through legislation.

There have been only eleven cases in the United States in recent times that have involved weather modification activities. These cases have resorted to the common law for guidance and none has found that weather modification was the cause of alleged damages. However, two cases did grant the plaintiff

injunctive relief in that they ordered a stop to the weather modification activities, but at least one case denied the same relief. This judicial experience under the common law does not give much guidance for cases that might arise in the future. If we were to let a law of weather modification develop under common law, we would run the risk that the common law might not be able to proceed rapidly or boldly enough to cover the problems that the technology could produce.

Law-making bodies can, however, address some of the problems of a developing technology by enacting statutes. The federal government enacted Public Law 85–510, in 1957, which expressed a federal interest in and a basis for possible federal regulation of weather modification activities. Even though there has been concern and activity since that time in the federal government, except for a requirement to file reports on their activities with the National Oceanic and Atmospheric Administration, weather modifiers are under no federal regulation. The rate of technical development was too slow to interest the Congress in making new laws about weather modification.

The state governments, however, have been closer to the problem; they have taken note of the damage that could be caused by thinly financed, unscrupulous, or incompetent weather modifiers. Many states have enacted statutes requiring professional licensing, operational permits, or reporting and evaluation of weather modification activities. These requirements are by no means uniform from state to state. The three Upper Basin states—Colorado, Utah, and Wyoming—all have statutes related to weather modification activities. In early 1972 a weather modification control bill was enacted by the Colorado legislature. This law requires the prospective weather modifier to seek a permit and justify the project at a public hearing. Nevertheless, the general lack of an effective administrative apparatus for state regulation of weather modification activities has two implications: any federal legislative moves in the regulatory area would probably not interfere with state institutions;

there appears to be no base of expertise in the states upon which the administration of a federal regulatory system could rely.

The National Interest

The kind of WOSA program that we get in the Upper Colorado River Basin will depend upon the public policy that is made for it. However, there is an existing policy for Colorado River water resources, and there are existing policies for most other aspects of a full-scale WOSA program. What we have is a fabric of public policy with a hole in it—weather modification.

The freedom that we have in shaping an adequate public policy for weather modification is limited. The facts suggest that the federal government has a continuing responsibility for the WOSA program, based on one aspect or another of the national interest:

Ecological and environmental impacts

Disasters such as flooding

Adverse interstate precipitation effects and interstate allocation of atmospheric moisture

National water resources planning and Colorado River augmentation

Continued long-term monitoring of the effects of WOSA

Continued cloud-seeding research and pilot program experimentation

The least amount of authority that the federal government must exercise to meet its responsibilities would result in the federal government becoming a regulator. If the federal government must become a regulating authority because of its responsibilities in a WOSA program, it should (and probably will) consider extending this authority over all possible types of weather modification activities. The effects that would be in the national interest may change from one form of weather modifi-

cation to another. However, there are national interests that demand a minimum federal responsibility that can be discharged through a regulatory function.

Conflicts of Interest

The federal regulatory powers for weather modification should be placed in a regulatory board that is independent of existing or proposed research and operating authorities. This independence for the regulatory board would have several advantages. By ensuring that the minimum federal responsibility was being discharged by the regulatory board, the federal government would have a great deal of flexibility in setting up the Upper Basin WOSA operating program. The regulatory board would offer the least interference with the decisions of operating authorities, but would provide a centralized authority for resolving conflicting interests, whether the operating authority is the federal government or another entity.

Some might argue that the creation of another federal governmental body is unjustified, since there is plenty of experience and expertise within the Bureau of Reclamation or the National Oceanic and Atmospheric Administration to conduct a safe and responsible cloud-seeding program. However, both of these agencies were created to carry out specific jobs. They might have a difficult choice to make when their job or mission conflicted with the national interest aspects of WOSA.

As an example, the weather modification activities of the Bureau of Reclamation demonstrate two characteristics of such mission-oriented agencies that demand independent federal regulation:

> The mission-oriented agency will tend to isolate weather modification technology from public scrutiny during the time it is conducting research and experimentation.
>
> The mission-oriented agency will tend to favor its primary responsibilities and mission.

Weather modification must be regulated with the highest degree of objectivity of which we are capable. One natural disaster in a seeded area, whether related to weather modification or not, could set back the technology for many years. To a large degree the Upper Basin WOSA program may be the medium through which many of the concerns, institutional conflicts, and technical problems of weather modification in general will have to be resolved. An independent regulatory board seems to be indispensable if this undertaking is to have any chance at all.

Powers of a Federal Regulatory Board

To discharge the federal responsibility, a federal regulatory authority should have powers that cover the following aspects of a WOSA program in the Upper Colorado River Basin:

- Power to license the technology of weather modification, including the equipment and the materials used
- Power to license operators to ensure that they can meet the minimum federal requirements for capability and responsibility
- Power to require research and monitoring as a condition of operations, as well as giving the operator the right to conduct such activities that he may deem necessary to the operations
- Power to set environment and ecological standards that the program must meet
- Power to establish minimum operational criteria to protect the health and safety of people living in the target areas
- Power to stop the program at any time and to require substantial modification as a condition of its further continuation
- Power to require contributions to Federal or state disaster funds

To license weather modification operators, it is necessary to develop professional standards and some means for certifying that these standards are met. In addition, the candidates for

licensing may have to show financial responsibility. Only those key personnel who will make the decisions to seed will require licensing. If these decisions are made in a centralized location for all of the target areas, then only a very few persons need be licensed. However, if the seeding decisions are made on a local basis, key personnel in each operating district would need to be licensed.

If an agency of either the federal or state government operates the WOSA program, then the extent of financial responsibility may be set by law. If the program is contracted to private operators, the governmental authority may either assume financial responsibility or require the operator to provide insurance as part of his qualifications for obtaining a license.

All but the first two regulatory powers listed could be implemented by granting permits for specific weather modification operations. These permits would ensure that the minimum federal responsibility is met. The exact form of the operational permits would depend on who would be responsible for the program. For example, if a state or other governmental authority were to undertake the WOSA program, it would be entirely reasonable for the Federal Regulatory Board to issue the state a permit for a specified number of years, subject to conditions that would protect the national interests. These permits could specify the events or conditions that would annul them. They could also allow the delegation of operating authority to private contractors or to smaller governmental units.

There are several reasons for giving the Federal Regulatory Board the power to license the technology of weather modification, including the equipment, processes, and the material used. It is not reasonable to leave the matter of the proof of the adequacy, effectiveness, and safety of the weather modification means and materials used solely to the individual operator. The public health, occupational safety, and environmental effects of WOSA operations are all matters of national interest. The certification procedure could specify the conditions and limitations under which the equipment, processes, and materials could be

safely used. The certification procedure could also provide public assurance that as long as the specifications and standards were met, undesirable effects would be minimal.

Organizing a Full-Scale WOSA Program

The range of alternative institutions for a primary WOSA operating authority is limited, but within each of these primary operating authorities there is a fairly wide range of innovative possibilities for conducting the program.

Possible Operating Authorities

Two kinds of public policy decisions are to be made. The first determines the kind of operating authority that will be established. The second determines the best method of implementing the program under that authority. The public that will decide who is to be the operating authority is different from the public that will decide among the range of alternative policies within those authorities.

The Federal Government: Under this authority, the waters resulting from WOSA would be added to the Colorado River system as if they were natural waters. The Congress would, however, have the power to allocate the augmented waters as it saw fit. Under existing law, this power could be delegated to the Secretary of the Interior.

The tradition of public policy with respect to the Colorado River would require that the Bureau of Reclamation be authorized to operate the program. To suggest even modest innovations is to go against the trend of the existing institutions of the River. Nevertheless, WOSA in the Upper Basin has some

BASIC WOSA
OPERATING AUTHORITY

UPPER BASIN
TARGET AREA
STATES

WYOMING

UTAH | COLORADO

FEDERAL GOVERNMENT

WYOMING | UTAH | COLORADO

INTERSTATE COMPACT

AGREED .....
TO MAKE A FIRM
AUGMENTED WATER
SUPPLY .....
.....

COLORADO
WYOMING
UTAH
APPROVED: U.S. CONGRESS

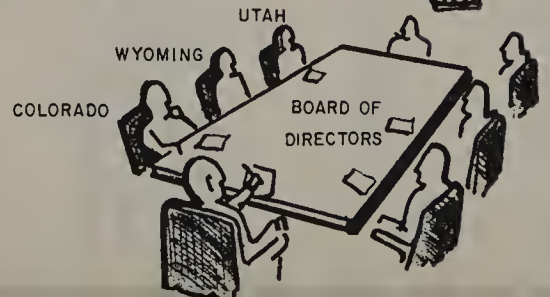
FEDERALLY
CHARTERED
CORPORATION

CHARTER
TO FORM A WEATHER
MODIFICATION DISTRICT
TO MAKE SNOW FOR
FUN AND PROFIT .....
.....

GRANTED BY
U.S. CONGRESS

DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION

DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION



unique characteristics that tend to deny the traditional approach. WOSA will place burdens on the people, institutions, economy, and environment of the Upper Basin, at a time when there is a growing national recognition that one segment of society should not be unfairly burdened for the measurable benefit of a different segment of society. It is not clear that the Bureau of Reclamation can separate its traditional role of "making the desert bloom" from the interests of the target area population.

The National Oceanic and Atmospheric Administration is also a possible operating authority, but it would lack the water distribution knowledge of the Bureau of Reclamation.

The States of the Upper Basin: The Congress could declare that the states may undertake a WOSA program, that the water produced is the exclusive property of the producing state, that the Bureau of Reclamation shall in its existing and authorized facilities store and distribute the augmented water, and that the Secretary of the Interior shall annually determine the amount of augmented water produced in each state. In effect, such Congressional legislation would give each state a marketable interest in the water it could produce, the water would not be subject to the Law of the River, and the state could dispose of its water as it saw fit (Figure 15).

If this authority were to be given to individual states, it might lead to problems between the producing states. In the Upper Basin, Colorado alone could produce enough water to justify its own WOSA program. However, it would be desirable if all the states that could produce WOSA water in the Upper Basin would join together in a unified program. Congress could, therefore, specify that Colorado, Utah, and Wyoming enter into an interstate compact; or Congress could grant the authority for operating WOSA to a federally chartered corporation (like the Tennessee Valley Authority) whose governing authorities could be appointed by the states involved.

Operating Authority Selection

The basic choice for a primary WOSA operating authority is between the federal government and the states of the Upper Basin. If any entity other than the federal government is to be the operating authority, Congress must legislate the ownership of the water produced. If Congress authorized a WOSA program and did not, at the same time, allocate the waters to be produced, then under existing law the Secretary of the Interior would allocate the water within the limits imposed by the Law of the River. As a practical matter, a state might claim ownership of WOSA-produced waters without a Congressional allocation. However, before it could use the water, the state would have to build storage and distribution facilities.

The maximum powers of ownership and domain that Congress could grant to an operating authority that was not part of the federal government are:

The unqualified right to use the water for whatever purpose it chooses

The unqualified right to transfer the right to use the water

The unqualified right not to create augmented water

However, Congress would probably want to specify degrees of ownership and dominion which would be less than the unqualified ones listed above. For example, the right to use water would undoubtedly be limited to beneficial use and waste would not be tolerated.

The capital and operating costs of the WOSA program would be paid by the operating authority, and the revenues from the sale of augmented waters would accrue to the authority. If the operating authority were not a federal agency, policy decisions would be required because of the necessary federal involvement in the program. The federal government would not only perform regulatory services for the weather modification operations, but also federal water storage and distribution, and power generation and transmission facilities would be used.

Policy decisions would be needed to establish procedures for prorating costs incurred by the federal government for its services. Similar policy decisions would be needed for prorating benefits (other than the revenues from water sales) generated by the augmented waters. Tangible benefits will result from hydroelectric power generation but there will also be intangible benefits such as improved water quality and enhanced recreational opportunities. The possibility of offsetting some of the federal costs with these national benefits should be explored as a matter of policy.

Since it will be impossible to distinguish water added by WOSA from natural water, a non-federal operating authority would need some legal mechanism for determining the amount of water produced annually by the WOSA program. It would need to know how much water it owns. (If the Bureau of Reclamation were the operating authority, there would probably be no need under the existing Law of the River to determine the annual WOSA runoff for water allocation purposes.) To preclude conflicts between governmental entities, and also to prevent direct conflicts of interest in determining the amount of augmented water, it is recommended that the authority to determine how much water WOSA produces be placed in an independent body such as a Federal Weather Modification Regulatory Board.

The policy questions concerning the need for augmented water in the Colorado River Basin are different for a federal operating authority than for a non-federal operating authority. The issue that is most relevant to the federal operating authority is whether or not there is a long-term shortage of water in the river. For a non-federal operating authority, the important question is whether or not there is a demand for the water at a price at which it can be delivered.

The federal government can, as a matter of national policy, invest in water supply augmentation as a way of creating a future long-term demand for water in the basin. These investment decisions are based on policy decisions concerning the

growth of the nation and the region. This policy of creating a future demand has implications for the choice of a federal operating authority for WOSA. This choice would make WOSA a way to continue federal investments in future water needs in accordance with long-term growth projections for the basin, even though these growth projections could then become self-fulfilling prophesies.

There is a growing loss of public confidence in the policy of generating growth where none would naturally occur. That is one reason why the decision to authorize a major augmentation project for the basin is stalled. The Colorado River Basin Project Act of 1968 postponed any near-term decisions to authorize the enormous investments required to create a major augmentation source. In effect, Congress pushed the decision on major augmentation means closer to the time when the facts of shortages would become more certain. This has also dangerously shortened the time available to build the facilities should a shortage actually develop. In this situation a non-federally operated WOSA program provides two important advantages. First, the WOSA program could provide an augmented water supply to meet any growing shortages until the need for major augmentation becomes apparent. Second, by providing competition to the existing and almost exclusive developer of the basin's water supply—the federal government—the non-federal operating authority would tend to place the continuing question of a water shortage in a more objective light than is now the case. The non-federal authority would have to take the market as it finds it; no market would obviously mean no shortage.

There are several policy questions concerning water use that must be answered in evaluating the relative advantages of a non-federal operating authority over a federal authority:

> Should the WOSA water be allocated for use exclusively within the states in which it is created, or should each state be permitted to determine whether it wishes to use the augmented water or sell it out-of-state?

Are there identifiable near-term needs for additional water in the Colorado River Basin? If so, what type of operating authority would best serve them?

How is a non-federal operating authority to be protected from federal preemption of its water markets?

How are the water markets to be structured so that existing federal investments in storage and distribution facilities are not to be jeopardized by a non-federal operating authority?

Serious consideration should be given to empowering any WOSA operating authority to delegate parts of its authority to another unit of government or, possibly, to a private enterprise. Establishing this power greatly affects the flexibility with which other policy issues may be dealt. The particular form, limits, and extent of the power to delegate authority will depend on both the choice of operating authority and the choice of which issues are important to the public that will be involved.

Should a non-federal entity be authorized to operate the WOSA program, a number of existing federal interests would be affected:

The target areas for WOSA are predominantly federal lands.

The federal government has a vast investment in water storage and distribution works in the basin that is tied to a schedule of reimbursement by water users.

A national interest exists with respect to satisfying the Mexican Treaty obligation.

The federal government has a continuing investment in weather modification research and experimentation leading to an operational WOSA program in the Upper Basin.

Some way must be found to accommodate these interests. There are state interests in state water resources that must be taken into account if a non-federal operating authority is chosen. Congress could deal with some of these interests in any authorizing legislation, or the decision to reach the necessary

accommodation could be left up to the state as part of its decision to implement a WOSA program.

The Form of an Operating Authority

There are two possible non-federal operating authorities—the individual states of the Upper Basin, and an interstate compact of the states of the Upper Basin—and a quasi-federal entity that is classed as non-federal—a federally chartered corporation whose board of directors would include representatives of the states of the Upper Basin.

If each state was to be the WOSA operating authority within its own territory, each state would bear the costs of its program and each state would have the right to use the water that it produces or to sell it outside the state or outside the Basin. This situation would offer the least conflict with state laws and institutions. For example, the state law of liability would apply instead of, possibly, a federal rule of settlement of claims. The public policy for carrying out the program and dealing with its effects could be tailored to fit each state's needs. If all of the augmented water is to be used in the state in which it is produced, this is the best alternative.

Having individual states as operating authorities would have serious disadvantages if the augmented water were destined for use out of state or outside the Basin or for a joint pooling arrangement. If one state chose not to participate, or decided to pull out of the program after a year or two, it would defeat the purpose of the WOSA program to create a firm water supply. Other problems could arise among the states in the allocating of water to specific markets in individual states and in attempting any kind of centralized planning and operation of the program.

Congress could approve an interstate compact of Colorado, Utah, and Wyoming as a WOSA operating authority. The three states would agree jointly to undertake a WOSA program with the augmented water credited to each state according to the amount it produces. The interstate compact as an operating

authority can authorize the program on a truly regional basis and achieve the necessary interstate coordination to provide a firm augmented water supply. We feel that this institutional form is potentially adequate for carrying out the WOSA program in the Upper Basin. However, because of the need to obtain the agreement of the states involved and the consent of Congress to all of the specific details of the WOSA program functions, an adequate interstate compact may be difficult to form. These difficulties may delay the formation for a long time. Interstate compacts concerning water allocation among states have tended to cover areas in which only general agreements can be reached among the states and to which the Congress will consent. The settlement of important interstate matters by interstate compacts tends to lead to lawsuits rising out of the compact itself.

A more feasible alternative is for Congress to authorize the WOSA program through a federally chartered corporation. The corporation's governing body could be appointed by the states involved. There are different kinds of federally chartered corporations. One type remains essentially private although nonprofit, and usually performs humanitarian or patriotic functions —the Boy Scouts of America, for example. However, the type that we are considering is established to carry out what is essentially a governmental or quasi-governmental function. The Tennessee Valley Authority is perhaps the best-known example.

The federally chartered corporation has a number of advantages over the two alternative operating authorities that we have previously considered. The corporate structure is easily established and the conditions of operation can be tailored to meet the exact needs of the program. The corporate form is more easily amended than is the interstate compact. If Congress foresees the possibility that unexpected problems could arise, it can amend the provisions of the corporation by legislative action. The corporate form would permit the formation of an interstate weather modification district that is not necessarily a continuous geographic area, but several separate areas bound together as a unified authority. The corporation could be empowered to ap-

portion net revenues to each state for disposition according to priorities established by each state.

The federally chartered corporation would appear to be the most flexible institutional form to deal with the problems of apportioning the burdens and benefits of the program between producers and users of the augmented water. Finally, the corporation could represent many different interests on its board of directors by including representatives of the Upper Basin states, representatives of local units of government within those states, representatives of the Lower Basin states, and representatives of the water users' associations.

The main disadvantage of the federally chartered corporation is that, of the three non-federal alternative operating authorities, it is the most disruptive or preemptive of existing state institutions. The state legislatures are not included in the decision to establish the WOSA program under this authority. However, there is precedent in the TVA, and the corporation can recognize state institutions and laws, and include representation of state and local interests.

Managing WOSA in the Public Interest

USUALLY a new technology is going full blast before society has had an opportunity to get ready for it. The result is that the institutions for operating, regulating, and controlling the technology are unwilling, insensitive, or unable to respond to all the affected interests in an equitable and even-handed way. Our institutions cannot respond with anything like the speed with which technology can change our lives.

Public Interest in Decision Making

The people who could be affected by a WOSA program or who could influence the form that it takes belong to a variety of social categories:

Social units at many levels from individuals to federal governmental entities that are involved in the issues related to the most important social attitudes concerning WOSA

Sectors of society defined by economic and demographic characteristics of the Colorado River Basin

Organizations and interest groups that have expressed public interest in weather modification, Colorado River Basin water resources, and related issues

Organizations and interest groups that have a relationship to the Bureau of Reclamation's Colorado River Basin Pilot Program or related weather modification activities.

Communities in the Upper Basin Target Areas

Those groups that identify with the national interest

A list of important issues was obtained by having a group of people with knowledge of the different aspects of WOSA in the Upper Colorado River Basin identify, from a tentative list of attitudes, those that were likely to be important factors in the program. The most important issues were:

Should the WOSA program be implemented?

Who has the right to decide if the WOSA program should be implemented, and who has, or should have, the authority to implement it?

How should the program be implemented and what are the possible (or probable) advantages and disadvantages (and to whom) of a full-scale WOSA program?

What modifications or additional provisions would make the program more acceptable?

A study of attitudes was made, based upon these important issues and concentrating primarily, but not exclusively, on target area residents. It revealed that WOSA is desirable as a source of augmented water for certain uses only if policymakers provide for controls over the WOSA program that give due consideration to the consequences for target area residents. There is general agreement that Congress has the right to establish weather modification policy, and that a WOSA policy should take account of effects that are detrimental to target area residents. However, advocates and opponents of WOSA do not agree on specific mechanisms for implementing this policy. Advocates oppose allowing target area residents to limit cloud-seeding through litigation, and they oppose making federal grants available to reimburse state and local governments for extra expenses resulting from WOSA. Opponents of WOSA favor both measures. There is disagreement on the need for policy regarding economic impacts of WOSA—for example, who would absorb the loss if the summer tourist season is shortened?

The public desirability of WOSA depends upon the type of policy that is established to control the social consequences of WOSA. The kind of controls that may be necessary for a socially desirable WOSA program are illustrated in the following recommendations:

Keep regulatory control out of the hands of advocates or opponents of WOSA. Establish an independent federal weather modification regulatory board to protect public and private interests in the target area, and to restrict public and private interference with the WOSA project.

Control seeding operations to limit precipitation in vulnerable areas.

Maintain a public information program meeting the needs of interest groups, and warning vulnerable groups about potentially undesirable effects.

The social desirability of WOSA can be determined only after a particular social policy has been applied. Although policies can be set up beforehand, based on analysis of attitudes and their consequences, change and flexibility should be built in. This feature requires a continuous assessment of social attitudes that can help to reform public policy throughout the life of the project.

The major underlying concern of the public is whether or not they will have a voice in any of the decisions about a WOSA program that will affect their lives. It appears essential to establish some means by which the affected publics can be brought into these decisions. To do this will require setting up entities whose characteristics distinguish them from the primary operating authorities:

Their authority is derived from the operating authority. Therefore the kinds of entities that can be established depend upon the operating authority chosen for the program.

The public involved in deciding whether to establish these entities is different from that involved in authorizing the WOSA program. The selection of the operating authority, whether by

an action of Congress or through default by a failure of Congress to act, is a decision in the national interest. These entities, on the other hand, deal with regional or local interests.

Most of the entities would be set up to deal with problems that result from deliberate enhancement of the snowfall in the target area.

The attitudes of the people in the target area toward an operational WOSA program can range from unqualified opposition—no WOSA at any price—to a concern that some undesirable effect will occur. For example, if there is a concern that additional snowfall will increase the avalanche hazard, the entity could deal with those concerns so that the impacts are reduced or are balanced by offsetting benefits.

If all of the people in the target areas were reasonably well informed of the known facts concerning the effects of WOSA, their concerns regarding the impact of these effects on their lives would be the best way of identifying problems with which the operational program must deal. There is a real need to translate all of the facts of WOSA so that an adequate public understanding develops. There is also a need to determine the public's concerns regarding the effects of WOSA as they understand them. All of their questions should be answered, even those that appear to be based on a lack of information or a misunderstanding of the facts. Should the people raise questions for which answers are not available, adequate assurances should be given that the program will only go forward in a conditional way: a monitoring program will be established for uncertain effects, and control authorities will agree to modify or terminate the program if undesirable effects are found. It should be made clear that these monitoring procedures and control authorities are being set up because of the concern of the people, and that the information produced will be made available to the people.

This kind of information exchange program should be implemented as soon as possible, so that it can influence the planning of the operational program that is already taking place. The

goal of this information exchange program is a relationship wherein the operational program is responding to social concerns based on a detailed, sophisticated, and objective understanding of the facts. The day is long past when a public works operating authority can either fail to inform the public of the effects of its projects, or ignore public concerns about them.

Formal public hearings do not seem to be an effective information exchange vehicle for such a program, because there is no exchange of views, but only a documentation of views. Often, only the most extreme viewpoints are presented. Worst of all, public hearings are held so late in the project formation that they may serve only to record a highly polarized public attitude that may or may not be based on facts.

Informal hearings—in the nature of a workshop or a working session—are considered to be a superior means for information exchange. The method will have to be designed to meet the needs. Representatives from each target area community could be nominated by the community or by local government to attend periodic workshops. Between workshops, the community representatives could be an effective link between the community and the WOSA operating authority, to pass on concerns, questions, and any emerging doubts (Figure 16).

Educational teams might also make a regular circuit of the affected communities, telling the people of the target area the facts of the program and listening to the concerns of the people. Such teams might be staffed from the state educational system, federal environmental educational programs, or the recommended Federal Weather Modification Regulatory Board. This regulatory board would have a major need for determining social concerns, but it could jeopardize its independence and credibility by becoming enmeshed in the workings of the program.

Another kind of entity would be needed to allocate any net revenues of the WOSA program. The WOSA program does not have to be a revenue-producing activity. For example, if the augmented waters were allocated to the Mexican Treaty, the

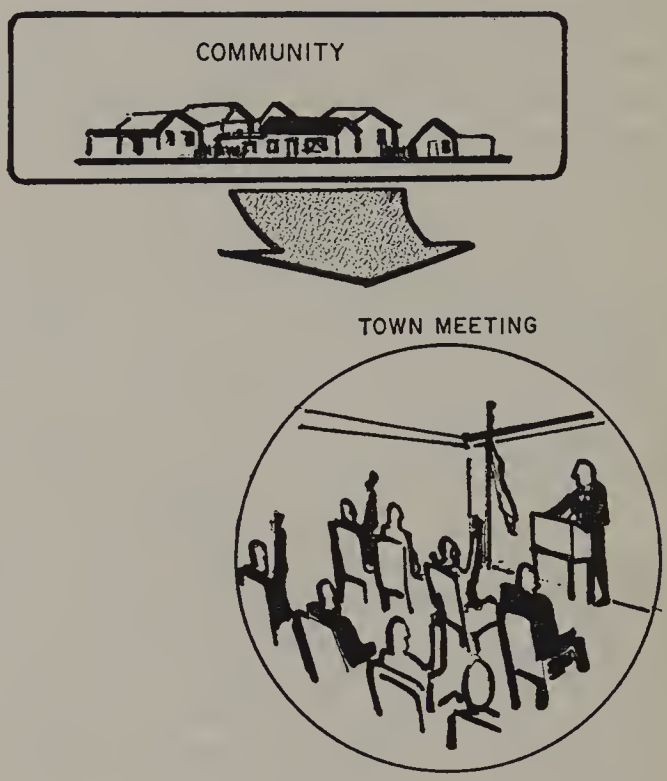
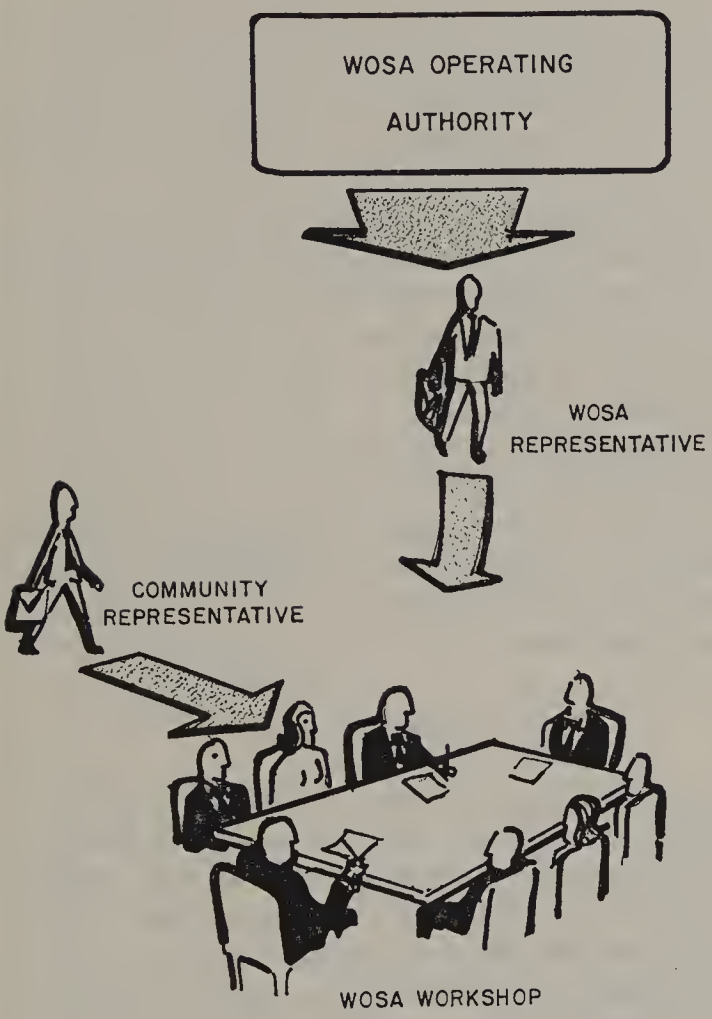


Fig. 16. How the public might participate in the WOSA decisions

water released for domestic purposes would be allocated by the Law of the River. According to the Law of the River, any revenues produced by the augmented water would go to reimburse the United States for capital and operating costs, and any surpluses to the Upper and Lower Basin Development Funds.

If Congress should authorize WOSA as a revenue-producing activity, then net revenues might be available to be distributed to compensate for perceived economic damages. This



possibility is a public policy decision, and the damages are not the kind that can be determined accurately or recovered by legal action—damages done to the general economy, or to one sector such as mining. The amount available for distribution depends upon the net revenues from the sale of water after allowing for costs. The allocation of net revenues to perceived but not legally recoverable damages could be made by one of several authorities. The distribution of discretionary revenues could be made

directly by the WOSA operating authority, but this could prove disruptive to existing local governments. Existing local governments could be designated for decision making. However, the jurisdictions of local governments do not coincide with the areas affected, and the jurisdictions often overlap. Another alternative would be formation of weather modification revenue districts for the purpose of establishing a decision-making public to allocate discretionary revenues. Regardless of the alternative chosen, rules should be established and approved for the allocation of net revenues so that they are spent for the purposes for which they were made available.

We have outlined different alternatives for establishing an information exchange program to deal with social attitudes, or for distributing net revenues from the sale of water to alleviate economic hardship in the target area. We suggest that two or three sets of alternatives for each be considered and voted by the people of the target areas.

Damages and Liability

A major unsolved public policy issue is the question of the extent and kind of liability to be incurred for weather modification. Courts have limited experience in the matter. Under existing theories of liability law—negligence, extra-hazardous activity, strict liability, trespass, nuisance—there have been no cases to date in which damages were recovered for weather modification activities. A special panel studying the legal problems of weather modification recommended that all weather modifiers be subject to the rule of absolute liability; operator negligence need not be proved, but the weather modification activities must be proved to have been the cause of damages.

From the strictly legal point of view, the major issues are concerned with the problems of proof. Given time and many cases, the law will absorb, digest, and resolve the facts of damages and develop adequate theories and rules for dispensing justice in the matter. However, on the basis of present knowl-

edge, the effects of nature cannot be separated from the effects of man. The problem is that the consequences cannot be connected to incidents of weather modification closely enough to meet the court's requirement of proof.

Some lawyers claim that the difficulty of proof according to existing legal standards is a continuing demonstration of the absence of actual compensable injury. Under this theory, only if liability and damages prove to be legally compensable should weather modification become a liability-producing activity. Other lawyers claim that a new rule of law is needed for weather modification activities to redress the potential damages from such activities. A third point of view is that we are dealing with a technology that may set off a chain of damage consequences quite incidental to the calculated benefits of the program. Although common law may eventually provide a suitable solution, there is good reason to anticipate and accelerate these legal developments through deliberate institutional means. The initiative for establishing liability for damages resulting from the proposed WOSA program must be taken by society and its institutions.

Examples of the kinds of damages that might result from a WOSA program are flood damages, calamities, and regional economic losses. It would be practically impossible to prove that WOSA caused a particular flood. The accumulated snowpack—both natural and augmented—is only one of many factors contributing to flooding. Congress has established a National Flood Insurance Program as a national policy, and serious consideration should be given to integrating this program with the WOSA program. The increase in insurance premiums that could be attributed to WOSA activities could be paid from the revenues from the sale of WOSA water. A federal disaster program designed to provide relief for major natural disasters also exists. This fund could be added to by WOSA-generated revenues and WOSA relief could be integrated with existing Federal relief legislation.

Appendix

THE technology assessment study on which this book is based was conducted by a team from Stanford Research Institute and the University of California at Davis with the assistance of eminent consultants.

Individuals who contributed directly to the project report are as follows:

Individual	Project Responsibility
George D. Hopkins	Project Manager
Leo W. Weisbecker	Project Leader
Roy M. Endlich	Task Leader—Weather Modification
Frank L. Ludwig	Meteorology—Weather Modification
Paul F. Paskert	Cost Analysis—Weather Modification Systems
Lynn Seaman	Avalanche Hazard Control
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David Storm*	Water Quality
Ernest C. Harvey	Task Leader—Economic Impact
Ronald L. Promboin	Economic Impact—Area of Origin
William W. Delaney	Economic Impact—Transportation
Richard J. Hammond	Economic Impact—Water Supply
Richard E. MacDonald	Electrical Power Benefits
Omar E. Snyder†	Economics of Silver
Allen W. Knight*	Ecological Impact—Aquatic Organisms
William M. Longhurst*	Ecological Impact—Wildlife
Ming-Yu Li*	Toxicology—Silver Iodide
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Robert A. Young, Colorado State University, Economics of Irrigated Agriculture

Experts on different aspects of cloud physics and precipitation modification who were contacted by telephone or by brief visits for general opinions or specific information that was otherwise unavailable are listed below. The information obtained from them is incorporated in appropriate sections of the report.

Prof. P. W. Mielke, Jr., Colorado State University
Prof. A. H. Auer, Jr., University of Wyoming
Prof. L. J. Battan, University of Arizona
Prof. R. R. Braham, University of Chicago
Dr. A. S. Dennis, South Dakota School of Mines
Prof. L. F. Radke, University of Washington
Dr. J. L. Rasmussen, Colorado State University
Dr. P. St. Amand, Naval Weapons Center, China Lake, California
Prof. V. J. Schaefer, State University of New York at Albany
Dr. Patrick Squires, University of Nevada
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Prof. D. L. Veal, University of Wyoming
Dr. Joseph Warburton, University of Nevada
Prof. M. C. Williams, Fresno State College

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Given adequate answers to these questions, we can make sound decisions about what the WOSA program should be. For the general reader this book tells the basic story of the findings detailed in the 600-page technical report by Stanford Research Institute for the National Science Foundation. For those who wish to pursue the technical findings, the complete report, *The Impacts of Snow Enhancement: Technology Assessment of Winter Orographic Snowpack Augmentation in the Upper Colorado River Basin*, is also published by the University of Oklahoma Press.

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